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Report Documentation Page

Report Documentation Page	Form Approved OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**
4. TITLE AND SUBTITLE **Improving Army Basic Research: Report of an Expert Panel on the Future of Army Laboratories**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **RAND Corporation,Arroyo Center,1776 Main Street, P.O. Box 2138,Santa Monica,CA,90407-2138**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**136**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Improving Army Basic Research

Report of an Expert Panel on the Future of Army Laboratories

PANEL ON THE FUTURE OF ARMY LABORATORIES

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Prepared for the United States Army

Approved for public release; distribution unlimited

RAND ARROYO CENTER

The research described in this report was sponsored by the United States Army under Contract No. W74V8H-06-C-0001.

Library of Congress Cataloging-in-Publication Data

Improving Army basic research : report of an expert panel on the future of Army laboratories / Gilbert Decker ... [et al.].
p. cm.
Includes bibliographical references.
ISBN 978-0-8330-5974-1 (pbk. : alk. paper)
1. U.S. Army Research Laboratory—Evaluation. 2. Military research—United States—Evaluation. 3. United States. Army Research, Development, and Engineering Command. 4. Laboratories--United States--Evaluation. I. Decker, Gilbert F. (Gilbert Felton), 1937- II. Rand Corporation.

U394.A34I53 2012
355'.070973—dc23

2012011327

Published 2012 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
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Preface

The Army is in the midst of an unprecedented technical transformation as it rapidly adopts the cutting-edge science and technology necessary to remain an effective fighting force. In this era of accelerating innovation, it is likely that many of the new concepts needed to make the Army's transformation a reality will only be realized through the discovery and application of breakthrough research and development (R&D).

This report describes the result of an expert panel assembled to consider how current trends in R&D might unfold over time and how those trends could affect the laboratories and R&D centers that support the Army. The panel focused primarily on basic, or exploratory, research conducted at laboratories and research, development, and engineering centers run by Army Materiel Command, from which cutting-edge discovery, invention, and innovation might emerge. The panel's inquiry was centered on the following question: "How can the Army get the best long-term value from its investments in basic research?"

This research was sponsored by the Director for Research and Laboratory Management within the office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology and focused on the laboratories and research, development, and engineering centers run by Army Materiel Command. It was conducted within the RAND Arroyo Center's Force Development and Technology Program. RAND Arroyo Center, part of the RAND Corporation, is a federally funded research and development center sponsored by the United States Army.

The Project Unique Identification Code (PUIC) for the project that produced this document is SAALT08864.

For more information on RAND Arroyo Center, contact the Director of Operations (telephone 310-393-0411, extension 6419; FAX 310-451-6952; email Marcy_Agmon@rand.org), or visit Arroyo's website at http://www.rand.org/ard.html.

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Background and Purpose

This report describes the result of an expert panel, referred to in this report as the Panel on the Future of Army Laboratories,[1] assembled to consider how current trends in research and development (R&D) might unfold over time, and how those trends could affect the laboratories and R&D centers that support the Army. The panel was convened based on the idea that the U.S. Army will be in the midst of an unprecedented technical transformation for the foreseeable future as it rapidly adopts and adapts to cutting-edge science and technology to remain an effective and relevant fighting force. In this era of accelerating innovation, it is likely that many of the new concepts needed to make the Army's transformation a reality will be realized only through the discovery and application of breakthrough R&D. Therein lies a potential challenge for the Army's R&D planners.

To support future decisionmaking by those planners, the panel focused primarily on basic, or exploratory, research from which cutting-edge discovery, invention, and innovation might emerge, although the panel also examined, to some degree, applied research and technology development—the other two components of science and technology (S&T). The panel focused on the following question: "How can the Army get the best long-term value from its investments in basic research?"

Most of the recommendations made by the panel and documented in this monograph are within the Army's power to execute. However, some will need the support of the U.S. Department of Defense (DoD) and even Congress. The panel believes that the large uncertainties in the threat that the nation will face in the coming decades make it imperative for the Army to improve the quality of its basic and applied research.

This research was sponsored by the Director for Research and Laboratory Management within the office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology and focused on the laboratories and research, development, and engineering centers (RDECs) run by Army Materiel Command (AMC).

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1 Although the expert panel did not have a formal name, for the purpose of this report we will refer to it as the Panel on the Future of Army Laboratories.

Panel Composition and Methods

A panel approach was directed by the research sponsor, who also approved the panel chairman selected by RAND Arroyo Center management. The Panel on the Future of Army Laboratories consisted of people who have spent their careers in research and managing research; or in the acquisition arena, where they oversaw or were consumers of research; or both. The panelists have experience in the Army, the U.S. Department of Energy (DOE), academia, and the private sector.

The panel's approach was to focus on collecting and examining available data that would reveal national trends in basic research and R&D, both federal and in the private sector, including the trends in investment in basic research and S&T and the pool of scientists and engineers (S&Es) that could be employed in these fields. The panel also examined trends in DoD's basic research and S&T funding, including the Army and other services. In particular, the panel focused on trends within the Army S&T establishment—the Army research labs and RDECs.

To get at the issue of the quality of basic research in the Army, the panel examined several laboratories known for their high-quality basic research: the three DOE nuclear weapon labs (Los Alamos, Lawrence Livermore, and Sandia National Laboratories), the Naval Research Laboratory, and AT&T's now-extinct Bell Laboratories. These labs have or had somewhat different missions than the Army's laboratories and RDECs and they operate or operated in different environments. But the environments that these labs created to stimulate high-quality basic and applied research provide some insights into how the Army might structure and fund its labs to improve the quality and value of its basic research.

The panel collected data from a variety of sources, reviewed relevant documents and reports, reviewed other laboratories for reference, and interviewed current and former researchers and leaders of Army laboratories and laboratories outside of the Army. The interviews were conducted on a non-attribution basis, so that the panel could receive the most candid information possible. RAND provided additional data collection and support for the panel to consider.

Findings

The Panel on the Future of Army Laboratories found—based on its analysis of data collected, the information gleaned from interviews, and reviews of the best basic research laboratories, as well as the panel members' collective experience in leading and managing research organizations—the following:

1. The environment for national and DoD research suggests the following:
    a. The United States, through the 20th century and the first few years of the 21st century, has led the world in basic research, but globalization could challenge this lead.

   b. Government-sponsored basic research has been critical to U.S. leadership in research, with DoD being a significant contributor.
   c. National defense has relied heavily on both nongovernment basic research and DoD-sponsored research to meet its needs.
   d. A reduction in DoD basic and applied research resources and also in non-government-sponsored basic research is forecast.
   e. Long-term defense capability, particularly in land warfare, will diminish considerably without a healthy basic and applied research effort.
2. Basic research should expand fundamental scientific knowledge that may lead to future warfighting capabilities. The Army needs a high-quality, inquisitive, agile basic research program with a long-term time horizon, in part because geopolitical futures and the needs of the future Army are uncertain.
3. The S&T domain is a continuum of discovery, knowledge, invention, innovation, technology development, and technology demonstration, with feedback cycles. It is often not a simple sequential process whereby an idea is started in basic research, migrates to applied research, and then transitions to technology demonstration.
4. The AMC basic research program is increasingly too near-term in its focus, with declining discovery and invention. In particular, the panel does not find mechanisms that stimulate staff to undertake high-risk but potentially transformational research in areas relevant to the Army.
5. Failure avoidance has grown to the point that research projects are expected to produce a product in addition to providing scientific knowledge. This has created a research, development, and acquisition (RDA) culture that trends toward conservative risk management at the expense of discovery, invention, innovation, and agility.
6. The Army S&T resources (funding, people, and facilities and equipment) database does not permit the necessary analysis and insights required by the Army S&T leadership to execute their policy, strategic, planning, oversight, and program defense responsibilities.
7. The metrics and data actually used by the Army Research Laboratory (ARL) for basic and applied research planning or evaluation are not apparent. There is a lack of metrics that allow ARL to track how the technology it develops is incorporated into new and modified systems. Thus, AMC cannot determine the return on its investments over the past 25 years, as evidenced by projects that eventually yield products and capabilities that are fielded.
8. The amount of basic and applied research funding available for the ARL Director to invest at his or her discretion, based on his or her local knowledge and capabilities, is far too low—below the 10 percent recommended in Chapter Five and Table 5.1 of this report. The ARL Director's Research, Quick Response, and Strategic Technology Initiatives are budgeted at only $7 million annually, from a core research budget of $174 million for in-house research in 2009.

Approximately 75 percent of ARL's core applied research funding is committed to Army technology objectives (ATO)s and technology program agreements (TPAs).

9. The share of the Army's basic research funding allocated to In-house Laboratory Independent Research (ILIR) has been declining since 1997 and has fallen below the 5 percent guidance from the Office of the Secretary of Defense (OSD) and the 5–10 percent goal recommended by the 1983 Packard report.[2]
10. Technical talent and management attention is a finite resource and must be managed accordingly. The panel finds that too much of ARL technical staff time and management attention is devoted to the pursuit of funding from external clients at the expense of leadership of ARL personnel and management of mission-funded basic and applied research. While work on applied research (Budget Activity 6.2) and advanced technology development (Budget Activity 6.3) projects is a valid sign of connection to the ultimate customer and of understanding of customer needs, the amount of basic research (Budget Activity 6.1) must be balanced accordingly and not neglected.
11. The recruiting, selection, career management, and development of S&Es requires more attention and innovation if the Army is to attract, retain, and mentor the staff necessary to meet its needs and perform high-quality S&T. The Personnel Demonstration Project, with its innovative provisions tailored to the scientist and engineer, is a demonstrated success at attracting and retaining good staff, reducing the time to fill openings, and permitting the lab to move in new directions more easily.[3] These features are vital to the quality of research organizations such as ARL and the Army Research Office (ARO).
12. The Army has not expanded its S&E workforce rapidly enough in the fast-changing research area of network and information sciences, where major breakthroughs continue to occur.
13. The percentage of ARL (less ARO) PhDs is far below the 50 percent typically found at first-rate laboratories, such as the Naval Research Laboratory (NRL), Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. The panel is also concerned about the low percentage of PhDs in the RDECs, which is only 2–5 percent at several of the RDECs.
14. The quality of research at ARL has steadily improved since its inception. However, the stature and extent of recognition of ARL research within the external research community have not improved commensurately. For example, there are currently no members of the National Academies at ARL. External recognition is important for attracting and retaining quality staff. As such, improving

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2 *Report of the White House Science Council Federal Laboratory Review Panel*, 1983. ILIR funding is provided to the RDECs, but not to the ARL.

3 The Personnel Demonstration Project was previously called the Laboratory Demonstration Program, and it is often referred to by that name.

ARL's standing requires significant attention from ARL and Army leadership. It also requires continuous tracking and assessment by research department leaders of the progress on research projects.

15. The list provided by ARL of major inventions during the past 25 years originating from ARL basic and applied research (not including ARO-funded research) was uneven, tended to be innovations rather than discoveries or inventions, and dated back beyond the last quarter century. Notable discoveries and inventions are an important output metric for a research organization. ARL's ability to tell its story in and out of government is vital to establishing its reputation, attracting high-quality staff, and demonstrating the value of its basic and applied research to the Army.
16. The ARL has neither metrics, nor an investment/modernization plan, nor a funding line for anticipated facilities and equipment needs. ARL does not know its facilities recapitalization rate. The Army funded modern ARL facilities at Adelphi and Aberdeen, Maryland, through the base realignment and closure (BRAC) process. However, the panel is concerned that investments and facilities are not being sustained at a rate that would make them competitive enough to attract new staff and flexible enough to move to new areas.
17. ARO has been placed organizationally under ARL, which reports to Army Research, Development and Engineering Command (RDECOM), which reports to the commanding general of AMC. This runs directly counter to the arrangements at the best research laboratories within and outside of government, where they report to the chief executive officer (CEO) or to the CEO through a chief technology officer (CTO). The panel observes that, given the long-range nature of research and how ARL has become increasingly near-term in its focus at the expense of discovery and invention, the benefits of placing ARL and ARO under a large intermediate command like RDECOM as opposed to reporting to the commanding general of AMC are not clear.

Recommendations

The Panel on the Future of Army Laboratories has developed, based on these findings, a number of recommendations that it believes will improve basic and applied research within the Army. (The numbers in brackets indicate the findings that correspond to each recommendation.)

1. The Army should establish a culture of discovery in basic research to encourage risk-taking and pursuit of opportunities with high potential, in part by providing incentives for experienced researchers to take greater risk in new areas of discovery. [2, 4, 8, 9, 10, 14, 16]

2. The Army should improve the quality of its basic and applied research by improving its agility to move into new areas quickly and to encourage and reward risk-taking by the research staff. [2, 3, 4, 15]
3. The Army should diversify its basic research portfolio and establish funding stability in order to restore a longer-term perspective for basic research planning. [2, 4, 9]
4. The Army should increase its S&E bench strength in the fast-evolving areas of network and information S&T, where the biggest advances are likely to come. Inspired senior scientists and technologists with vision will be essential in research as well as in the design, development, evaluation, and deployment of future systems. [12]
5. The Army should keep ILIR funding at or above 5 percent of the Army's 6.1 budget and execute it like the Laboratory-Directed Research and Development (LDRD) program at the DOE weapons labs, excluding taxing customers. [2, 9]
6. The Army should increase the amount of discretionary basic and applied research funding allocated to the director of ARL to 5 to 10 percent of its total basic and applied research budget, as recommended in the Packard report. ARL should not have more than 50 percent of its 6.2 mission funding obligated for TPAs and ATOs. [8, 10, 11]
7. The Army and DoD should institutionalize the Personnel Demonstration Project personnel management system and seek direct local hiring authority for S&Es. Lab managers should leverage this system to improve the quality of their staffing and the personnel flexibility in their organization. [11, 13, 14]
8. ARL should task a panel of distinguished scientists and engineers from outside the Army to identify the top 20 most important research inventions in the past 25 years from ARL (less ARO) and its predecessor organizations. This story should be captured in media suitable for distribution, to raise awareness among the R&D community in academia, industry, and government of the return on investment for ARL. This effort should be updated every five years. [14, 15]
9. The Army should continuously improve S&E quality, recruiting, and retention within a culture of merit via
    a. the vigorous use of internships, coops, postdocs, researcher mobility across budget categories, and training, exchange, and collaboration arrangements with industry and academia
    b. field training with operational units.
    c. mentoring junior and new S&Es.
    d. seeking external recognition of staff by encouraging publications, patents, and professional society fellowships. [11, 12, 14]
10. The Army should develop and fund a laboratory/RDEC recapitalization plan, including a recapitalization rate goal for each laboratory and RDEC that sustains the capital stock and technical equipment at a level commensurate with

world-class research facilities. This is intended to address the challenges of securing sufficient funding for capital equipment and facility construction. [6, 14, 15]

11. The Army-wide S&T resource database needs to be improved to support timely analysis and decisions for sound policy, strategy, planning, and program defense and oversight. [6, 7]
12. The Army should reconsider the reporting chain for ARL and ARO.
    a. The panel recommends that, at a minimum, ARL should report directly to the commanding general of AMC, as do the AMC major subordinate commands.
    b. Given the Army-wide nature of ARO, the panel recommends that ARO either (1) report directly to the Deputy Assistant Secretary of the Army for Research and Technology (DASA(R&T)) or (2) remain part of ARL except be under the operational control of the DASA(R&T). There is precedent for the recommended operational control, as the Army Research Institute is part of the U.S. Army Human Resources Command but under the operational control of the Deputy Chief of Staff, G-1. [4, 8, 9, 14, 17]

Acknowledgments

The panel would like to thank the many researchers and laboratory managers and directors that we interviewed during the study. The panel is also indebted to John Parmentola for commissioning the study and to the tireless efforts of Jagadeesh Pamulapati, Jeff Singleton, and Carolyn Nash for providing the necessary data, information, and contacts to conduct the study. The panel would also like to express its gratitude to Phil Kehres of RAND for making the panel meetings run so smoothly and for preparing this manuscript for publication. Finally, the panel would like to thank John Lyons of the Center for Technology and National Security Policy at the National Defense University and James Bonomo of RAND for their thoughtful review of the report and constructive suggestions. Of course, the panel is responsible for the contents of this report.

Abbreviations

A/JCTD	advanced/joint concept technology demonstration
AAAS	American Association for the Advancement of Science
ACOM	Army command
AFRL	Air Force Research Laboratory
AHS	American Helicopter Society
AMC	Army Materiel Command
AMRDEC	Aviation Missile Research, Development and Engineering Center
AMSAA	Army Materiel Systems Analysis Activity
ARCIC	Army Capabilities Integration Center
ARDEC	Armament Research, Development and Engineering Center
ARL	Army Research Laboratory
ARO	Army Research Office
ARPA	Advanced Research Projects Agency
ASTAG	Army Science and Technology Advisory Group
ASTMP	Army's Science and Technology Master Plan
ASTWG	Army Science and Technology Working Group
ATD	advanced technology demonstration
ATO	Army technology objective
ATO-D	Army technology objective—demonstration
ATO-M	Army technology objective—manufacturing technology

ATO-R	Army technology objective—research
BA	budget activity
BRAC	base realignment and closure
CAGR	compound annual growth rate
CEO	chief executive officer
CERDEC	Communications-Electronic Research, Development and Engineering Center
CTA	cooperative technology agreement
CTD	concept and technology demonstration
CTO	chief technology officer
DARPA	Defense Advanced Research Projects Agency
DASA(R&T)	Deputy Assistant Secretary of the Army for Research and Technology
DCS	Deputy Chief of Staff
DDR&E	Director, Defense Research and Engineering
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRI	Director's Research Initiative
DTRA	Defense Threat Reduction Agency
ECBC	Edgewood Chemical and Biological Center
ENIAC	Electrical Numerical Integrator and Calculator
F3	form, fit, and function
FCS	Future Combat System
FEDLABS	Federal Laboratory Consortium for Technology Transfer
FFRDC	federally funded research and development center
FY	fiscal year
GDP	gross domestic product
HQDA	Headquarters, Department of the Army
ILIR	In-house Laboratory Independent Research
IOT&E	initial operational test and evaluation

IT	information technology
LCMC	Life Cycle Management Command
LDRD	Laboratory-Directed Research and Development
LFT&E	live fire test and evaluation
LQIP	Laboratory Quality Improvement Program
MASER	microwave stimulated emission
MATDEV	materiel developer
MILCON	Military Construction
MIT	Massachusetts Institute of Technology
MURI	multidisciplinary university research initiative
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NNSA	National Nuclear Security Administration
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSRDEC	Natick Soldier Research, Development and Engineering Center
OS	Office of Science
OSD	Office of the Secretary of Defense
PE	program element
PEO	program executive officer
PM	program manager
PPP	purchasing power parity
QRI	quick reaction initiative
R&D	research and development
RADIUS	Research and Development in the United States
RDA	research, development, and acquisition
RDEC	research, development, and engineering center
RDECOM	U.S. Army Research, Development and Engineering Command

RDT&E	research, development, test, and evaluation
S&E	scientist and engineer
S&T	science and technology
SES	Senior Executive Service
SMDC	Army Space and Missile Defense Command
ST	senior scientist
STI	strategic technology initiative
STTC	Simulation and Training Technology Center
T&E	test and evaluation
TARDEC	Tank Automotive Research, Development and Engineering Center
TC	Technical Council
TPA	technology program agreement
TRADOC	U.S. Army Training and Doctrine Command
TRL	technology readiness level
TTA	technology transition agreement
UARC	university-affiliated research center
UCLA	University of California, Los Angeles
USACE	U.S. Army Corps of Engineers
VCSA	Vice Chief of Staff of the Army
WTC	Warfighter Technical Council

CHAPTER ONE

Introduction

This report describes the result of an expert panel, referred to here as the Panel on the Future of Army Laboratories,[1] assembled to consider how current trends in research and development (R&D) might unfold over time and how those trends could affect the laboratories and R&D centers that support the Army. The panel was convened based on the idea that the U.S. Army, now and for the foreseeable future, exists in the midst of an unprecedented technical transformation as it rapidly adopts and adapts to cutting-edge science and technology to remain an effective and relevant fighting force. In this era of accelerating innovation, it is likely that many of the new concepts needed to make the Army's transformation a reality will be realized only through the discovery and application of breakthrough R&D. Therein lies a potential challenge for the Army's R&D planners.

To support future decisionmaking by those planners, the Panel on the Future of Army Laboratories focused primarily on basic, or exploratory, research from which cutting-edge discovery, invention, and innovation might emerge, although the panel also examined to some degree applied research and technology development—the other two components of science and technology (S&T).

The panel did not examine the role of a healthy national S&T base for economic prosperity and security. Many other studies have done that and virtually all agree that a healthy S&T base is vital, so the panel took that as a point of departure for their analysis, focusing on the following question: "How can the Army get the best long-term value from its investments in basic research?"

This research was sponsored by the Director for Research and Laboratory Management within the office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology and focused on the laboratories and research, development, and engineering centers (RDECs) run by Army Materiel Command (AMC). The sponsor requested an expert panel approach to consider the challenges facing Army R&D planners. RAND supported the panel.

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1 Although the expert panel did not have a formal name, for the purpose of this report we will refer to it as the Panel on the Future of Army Laboratories.

Panel Composition and Methods

A panel approach was directed by the research sponsor, who also approved the panel chairman selected by RAND Arroyo Center management. The chairman then selected the panel members. The expert panel consisted of people who have spent their careers in research and managing research, or in the acquisition arena where they oversaw or were consumers of research, or both. They have experience in the Army, the U.S. Department of Energy (DOE), and the private sector.

The panel's approach was to focus on collecting and examining available data that would reveal national trends in basic research and R&D, both federal and in the private sector, including the trends in investment in basic research and S&T and the pool of scientists and engineers (S&Es) that could be employed in these fields. The panel also examined trends in the Department of Defense's (DoD's) basic research and S&T funding, including the Army and other services. In particular, the panel focused on trends within the Army S&T establishment—the Army's research laboratories and RDECs. This analysis revealed gross trends that might be of concern to the Army.

To get at the issue of the quality of basic research in the Army, the Panel on the Future of Army Laboratories examined several labs known for their high-quality basic research: the three DOE nuclear weapon labs (Los Alamos, Lawrence Livermore, and Sandia National Laboratories), the Naval Research Laboratory, and AT&T's now-extinct Bell Laboratories. These labs have or had somewhat different missions than the Army's labs and operate or operated in different environments. But the environments that these labs have created to stimulate high-quality basic and applied research provide some insights into how the Army might structure and fund its labs to improve the quality and value of its basic research.

The panel collected data from a variety of sources, reviewed relevant documents and reports, reviewed other laboratories for reference, and interviewed current and former researchers and leaders of Army laboratories and laboratories outside of the Army. The interviews were conducted on a non-attribution basis, so that the panel could receive the most candid information possible. RAND provided additional data collection and support for the panel to consider.

How This Report Is Organized

The rest of this chapter examines the value of basic research to the Army. Chapter Two provides an overview of the broad national and DoD trends in funding and human capital. Chapter Three provides an overview of the Army laboratory system, the trends therein, and the significance of those trends. Chapter Four outlines the characteristics of a top-quality research lab by examining several world-class research labs outside DoD. Chapter Five examines the implications of the trends in Army basic and applied

research, compares Army labs to the characteristics of the highly successful labs outside the Army, and recommends how these characteristics might be applied to improve the quality of Army basic research. Chapter Six presents the panel's findings, and Chapter Seven presents its recommendations. The report also includes several appendixes that provide background information about the Army's labs and the expert panel.

The Value of Basic and Applied Research

To address the value of basic and applied research, these terms must first be defined. In this study, the panel defined *basic research* as the quest for gaining knowledge about the fundamental aspects of physical phenomena, without specific applications in mind. The formal Army definitions of *basic research* (Budget Activity 6.1) and *applied research* (Budget Activity 6.2) are given in Chapter Three. Briefly, basic research is a systematic study that begins with a scientific hypothesis leading to a theory or an empirical exploration leading to a hypothesis. A research plan is then proposed to make measurements and gather empirical data to either prove or disprove the hypothesis. If the research plan is carried out and its result is solid proof or disproof of the hypothesis, then the research should be deemed successful. Applied research is a systematic study to translate promising basic research into potential solutions for broadly defined military needs. It is a systematic expansion and application of knowledge to develop solutions to meet the perceived needs. These brief definitions are consistent with DoD rules and instructions.

The question often arises, "What is the value of basic and applied research?" The very definitions above are self-evident in answering this question. Too often, the answer to the value is weighted with fiscal numbers. There is ample evidence in many studies that genuine technological progress depends heavily on basic and applied research, as is implied by the definitions. Within the scope of this study, the panel did not have time to conduct an exhaustive investigation of case studies to illustrate examples where basic research formed the basis of major advances in society, including national defense. The panel selected four examples where basic research sponsored by DoD formed the basis of major "game changers," both in society in general as well as in defense.

The first example is computer technology. Research by John von Neumann, a brilliant mathematician at Princeton University in the 1940s, conceived the concept of stored program computers based on his mathematical research. Based on this early research, the Army sponsored continued research by John Mauchly and J. Presper Eckert at the University of Pennsylvania. The research project was known as ENIAC 1 (Electrical Numerical Integrator and Calculator). The researchers conceived a digital computer architecture and then designed and constructed the ENIAC 1 computer. The ENIAC 1 was more than 1,000 times faster than calculating machines and could also be programmed to solve complex formulas that calculating machines could not

handle. Von Neumann was intimately involved in the whole project. A whole new industry was born with many commercial players, and, of course, the applications of computer technology to military needs are without bounds. Arguably, the computer generation may not have happened, or it may have been very slow in developing, or some other nation might have taken the lead, if the research had been left to purely commercial interests in the United States.

Second is the example of the development of ARPANet. The concept of ARPANet was based on some basic communications theory research called packet switching. This in turn was based on some basic research in queueing theory that was conducted by Leonard Kleinrock in the early 1960s while he was a student at the Massachusetts Institute of Technology (MIT). His work spurred early concepts of packet switching, and he further researched the concept of packet switching as a distinguished computer scientist at the University of California, Los Angeles (UCLA). From 1961 through 1964, Paul Baran, a RAND scientist, published a series of papers further defining the concept of packet switching. In 1963, J. C. R. Licklider, a scientist at MIT, was appointed to head a major division of the DoD Advanced Research Projects Agency (ARPA). Licklider had researched ideas for an "Intergalactic Computer Network," built on the theory of packet switching, as described in Baran's work. He and ARPA were intensely interested in creating a computer communications network. By 1968, a plan to create ARPANet was completed, and the project began. It was enormously successful and validated the concept of packet switching. From there, both the government and industry "took off," and the Internet was born. It would be stretching a point to say that, without ARPANet, the Internet would not have happened. However, it is safe to say that the DoD-sponsored work in packet switching and ARPANet was a major contributor to the birth of the Internet and to many eventual defense applications.

The third example is the development of the laser. The theoretical basis for the laser, which is an acronym for "light amplification by stimulated emission of radiation," was postulated by Einstein in a paper published in 1917. It remained an unproven theory until early work on microwave stimulated emission (MASER) by Charles Townes at Bell Labs and separately by Gordon Gould. They postulated the theoretical basis for stimulated emission in the light frequency range. Based on this work, the Pentagon awarded a research contract to the Hughes Research laboratories in Malibu, California, where Gordon Gould was employed. He and Ted Maiman, a Stanford University–educated physicist with a deep understanding of materials, knew that to prove the laser theory would require a material capable of storing energy briefly, then, upon stimulation, emitting the energy in a beam of light. Maiman succeeded using a synthetic ruby, and the theory of laser was verified. The work of Gould and Maiman was treated as just a scientific curiosity by many of their scientific peers. However, DoD continued to support laser research and was the critical factor in funding the incredible numbers of applications of the laser in all of society, and particularly in defense.

The fourth example is the area of semiconductor research. Semiconductor theory and its application have revolutionized the world in many respects. The trail of research that eventually led to the products we see today is vast. Even in the 1800s, scientists such as Michael Faraday postulated some ideas about conductivity in materials other than metals; but semiconductor research languished with the invention of the vacuum tube, which enabled wireless radio communications. However, basic research in semiconductors to try to understand the phenomena continued in the 1930s and even in the 1940s during World War II. It received an impetus at Bell Labs during this period, tied to the work of William Shockley. The degree to which the government sponsored the research at Bell Labs is unclear, but the National Defense Research Council initiated a program based on the Bell Labs work that consisted of basic research efforts as well as application-oriented applied research efforts. It was not long before transistors were developed, which made vacuum tubes obsolete, and not long after that before integrated circuits replaced complex, discrete-component electrical circuits.

There are many more examples of how there would not have been real technological progress and applications without basic and applied research. These four certainly had dramatic impact on the world and national defense.

CHAPTER TWO

Science and Technology Trends

The panel was asked by the research sponsor to examine broad trends in international, national, and U.S. government S&T spending and human resources, as well as trends within DoD and the Army and to judge what those trends mean for the future of Army S&T in general, and basic and applied research in particular. This chapter presents the results of that analysis, focusing first on national trends and then on DoD and the Army. The conclusion of the panel, however, is that these broad trends, while useful to point to some challenges for the United States in maintaining a strong (national) position in S&T, are of limited use for examining the current state and likely future of Army basic and applied research.

National and International Trends in Science and Technology

There have been many studies of the trends in S&T internationally and in the United States, and most of them ultimately conclude that the well-being of advanced nations, particularly the United States, is critically dependent on a healthy S&T base (BankBoston, 1997; Holm-Nielsen, 2002; Solow, 1960).

However, there is a growing concern that the U.S. position as the global leader in S&T is eroding. Several recent studies have documented this concern, including a 2007 report by a panel of the National Academy of Sciences entitled *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.[1]

A 2008 RAND Corporation report, *U.S. Competitiveness in Science and Technology* (Galama and Hosek, 2008), examined the concerns raised in the National Academy and other reports in detail, using available data. The results from that study portray a more nuanced and mixed picture in both funding and human resources. The

[1] Other studies include the National Association of Manufacturers' 2005 report *Looming Workforce Crisis: Preparing American Workers for 21st Century Competition*, the Task Force on the Future of American Innovation's 2005 report *The Knowledge Economy: Is the United States Losing Its Competitive Edge?* and the Office of U.S. Senator Joseph L. Lieberman's 2004 report *Offshore Outsourcing and America's Competitive Edge: Losing Out in the High Technology R&D and Services Sector*.

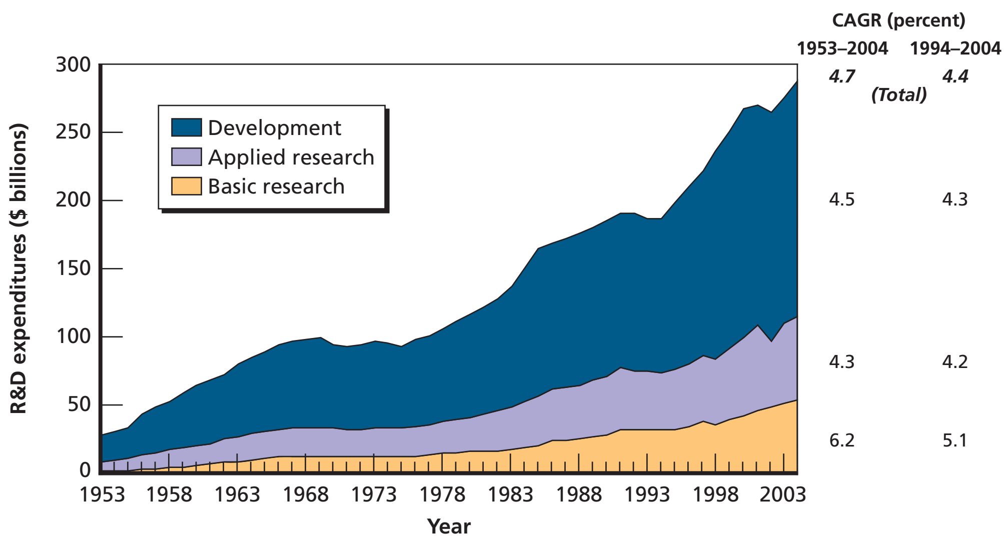
data in the following sections are drawn largely from the RAND study, which in some cases have been updated by the authors of that study and shared with the panel (Galama and Hosek, 2009).

R&D Funding

The first focus of concerns about U.S. R&D is funding. Looking at the trend in U.S. nationwide R&D expenditures from 1953 to 2004, it appears that overall R&D spending is very healthy (see Figure 2.1), growing at a compound annual growth rate (CAGR) of 4.7 percent over that period and 4.4 percent over the past decade. (The dollars in the figure and all figures in this study are in constant dollars; that is, they have been adjusted for inflation.) Basic research grew even faster, at a CAGR of 6.2 percent since 1953. It has slowed a bit since 1994, growing by only 5.1 percent per year, although this is still faster growth than for both applied research and development.

Much of the growth in R&D has been fueled by the private sector (see Figure 2.2), and while federal funding of R&D has grown, too, it has been much flatter, particularly over the past decade, where the compound annual growth rate has been only 1.9 percent. While the growth of private-sector R&D is a good thing, the limited growth in federal funding suggests a constraint in future DoD and Army funding. Indeed, DoD basic and applied research has fared relatively poorly over the past decade, both in absolute terms and relative to other federal S&T spending, as will be discussed later in this chapter.

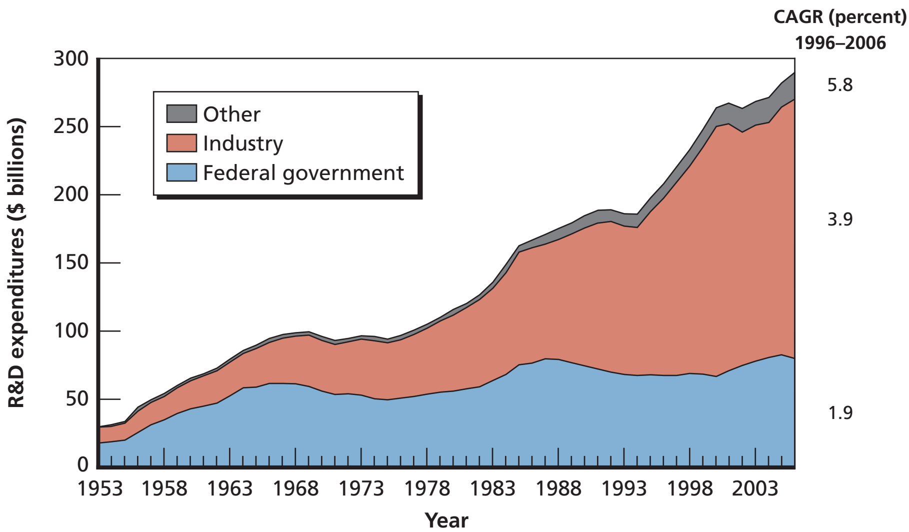
Figure 2.1
Total U.S. R&D Expenditures (constant 2000 dollars, billions), by Character of Work, 1953–2004



SOURCE: Galama and Hosek, 2008, p. 61.

RAND *MG1176-2.1*

Figure 2.2
U.S. R&D Funding, by Source, 1953–2006



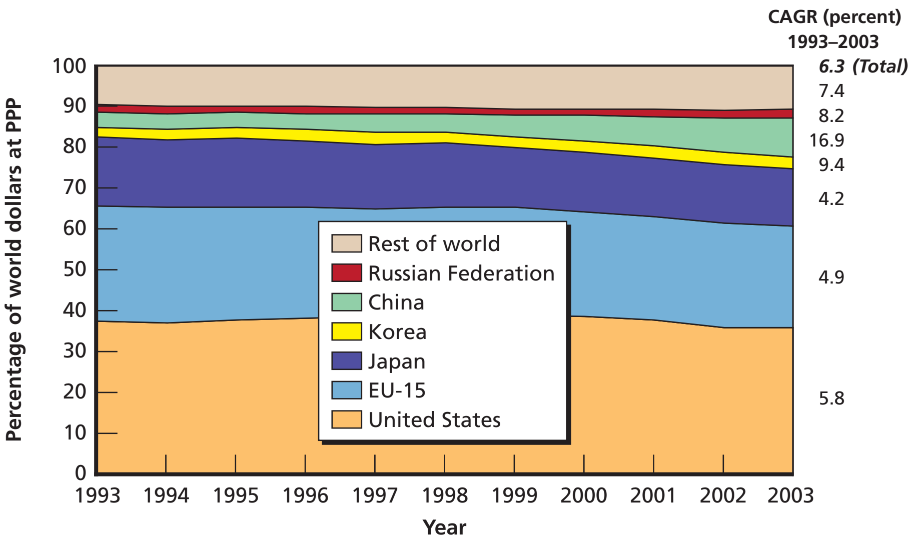
SOURCE: Galama and Hosek, 2009.
RAND *MG1176-2.2*

But how does U.S. R&D spending compare with that of other countries? Figure 2.3 compares international trends from 1993 to 2003: (1) R&D funding for several major nations from 1993 to 2003, in current dollars adjusted for purchasing power parity (PPP) as a percentage of the world total, and (2) CAGR of R&D expenditures. The U.S. share of world R&D expenditures in this ten-year period remained roughly constant, at around 35 percent. Note that China in the same period doubled its percentage of the world's total R&D expenditures, and its CAGR was almost three times that of the United States, although the share of Chinese R&D spending is still a fraction of U.S. spending.

Figure 2.4 shows a different comparison: gross R&D expenditures from 1985 to 2005 as a percentage of gross domestic product (GDP) for several of the same nations listed in Figure 2.3. The United States had a fairly constant percentage of GDP devoted to R&D during this period, a bit above 2.5 percent. Japan, Germany, and Korea spent a similar share of their GDP on R&D. China spent only about half as much, but it is increasing that share at the same time that its GDP is growing rapidly. It moved from a bit above 0.5 percent of GDP in 1991 to a bit above 1 percent by 2005. According to a new RAND study by Wolf et al. (2011), China is planning to increase the R&D spending to 2.5 percent of GDP by 2011.

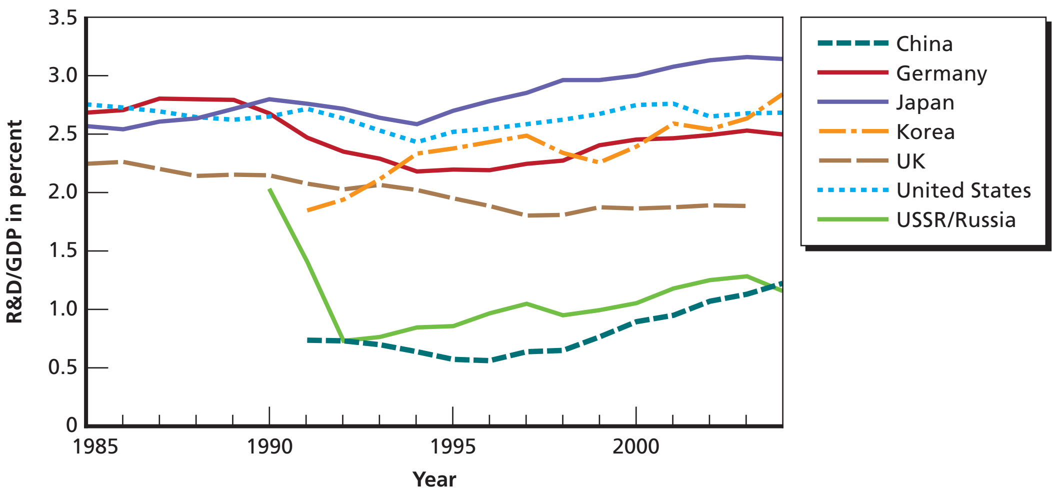
From an economic perspective, the data indicate that the United States has maintained its leadership in S&T expenditures through the first five years of the 21st century.

Figure 2.3
R&D Funding in Current Dollars at Purchasing Power Parity, 1993–2003



SOURCE: Galama and Hosek, 2008, p. 22.
NOTE: EU-15 = European Union 15, which consists of Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden, and the United Kingdom.
RAND *MG1176-2.3*

Figure 2.4
R&D as a Percentage of Gross Domestic Product, 1985–2005



SOURCE: Galama and Hosek, 2008, p. 23.
RAND *MG1176-2.4*

It should be emphasized that the comparative data contain all R&D expenditures, including S&T (basic and applied research), advanced technology development, and development of products for fielding. The data also include all sources of expenditures, both government and private. Thus, the data do not allow comparisons of the trends in basic and applied research, which is of more specific interest to the panel conducting this study.

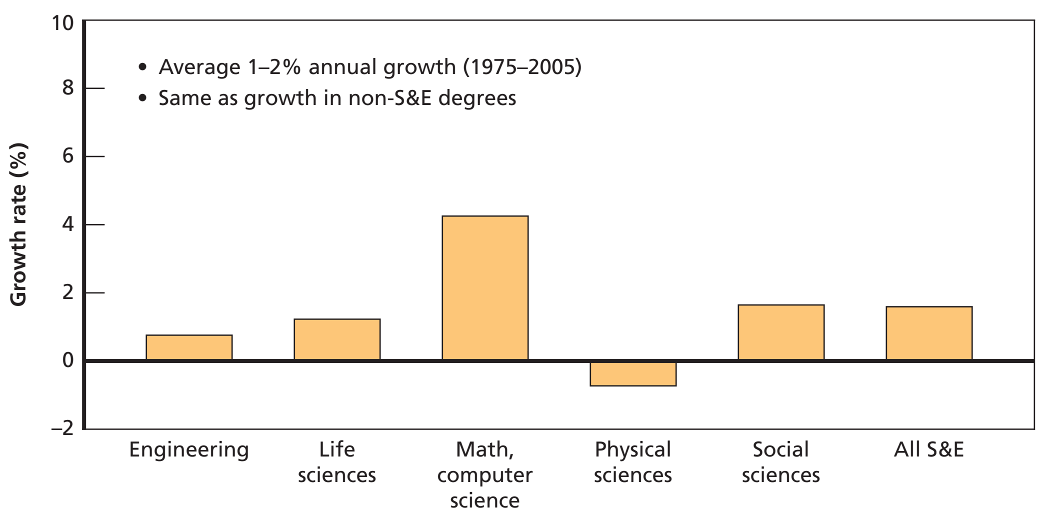
R&D Workers

The second focus of concern about U.S. S&T capability is centered on the workforce available to the U.S. S&T enterprise, particularly the number and degree level of S&Es and the rate at which they are being produced in U.S. universities. Figure 2.5 shows that the growth in the number of S&E degrees awarded by U.S. universities has been relatively modest from 1980 to 2000, growing at an average of 1–2 percent per year. While this seems low, it is roughly the same rate at which the number of non-S&E degrees is growing.

The modest production rate of S&Es is compounded by the fact that a large number of those degrees were earned by foreign students, particularly in engineering at the doctoral and master's level (Figure 2.6).

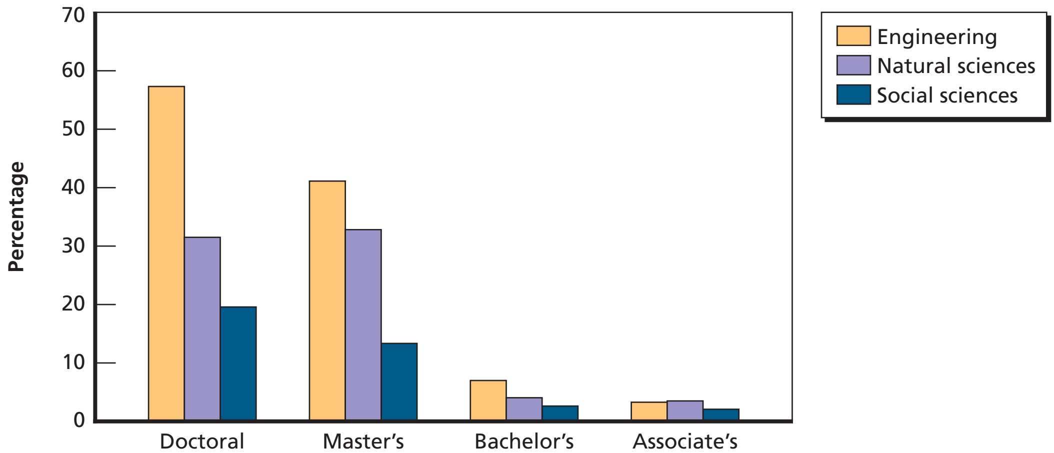
Slow growth in S&E production is so far not resulting in a shortage of S&Es; at least, there has not been an increase in S&E salaries that would reflect a shortage. Foreigners who come to the United States already trained are making up much of the

Figure 2.5
The Number of Science and Engineering Degrees Showed Modest Growth from 1980 to 2000



SOURCE: Galama and Hosek, 2009.
RAND *MG1176-2.5*

Figure 2.6
Foreign Students Are Earning a Significant Share of Science and Engineering Degrees



SOURCE: Galama and Hosek, 2009.
RAND *MG1176-2.6*

gap. While this appears to have been effective in meeting the shortfall in U.S.-grown S&Es, hiring foreign workers is not a solution that is usually available to the Army or DoD labs, which must rely on the pool of U.S. citizens for S&E jobs and must compete with industry to fill those slots. Unfortunately, there is a shortage of data that would allow an examination of the challenges that Army and DoD labs face in hiring quality U.S. S&Es. A particularly worrisome trend for the Army's labs, however, is the decline in the production of physical scientists (Figure 2.5), an area that has long been important to the Army and where the gap cannot be filled by noncitizens.

Federal, Department of Defense, and Army Trends

Given that the national trends in S&T spending (public and private) show strong U.S. investment and leadership in S&T, at least through the early years of the 21st century, the chapter compares the trends in basic and applied research by the federal government, DoD, and the Department of the Army.

Federal Spending

Federal spending on basic and applied research has experienced healthy growth since 1990 (see Figure 2.7). From 1994 through 2004, it grew at an annual rate of 5.3 percent, which is faster than the growth in national basic and applied research over the same period (about 4.6 to 4.7 percent, combining the growth rates for basic research and for applied research from Figure 2.1). However, this growth was dominated by increased spending by the National Institutes of Health (NIH) in the health sciences. With

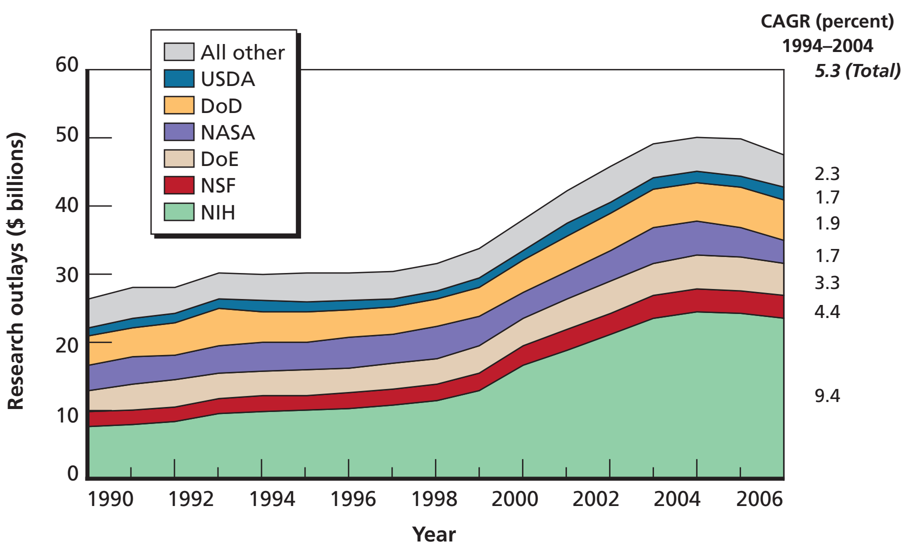
the exception of NIH and the National Science Foundation (NSF), all other federal outlays in basic and applied research grew slower than the total national growth rate. DoD basic and applied research has fared relatively poorly over the past decade, both in absolute terms and relative to other federal S&T spending. DoD funding for S&T has grown an average of only 1.9 percent per year over the past decade, only one-fifth the rate of funding for NIH during that period. By contrast, DOE S&T funding grew at 3.3 percent per year over that period.

Two issues of concern to the Panel on the Future of Army Laboratories arise from these trends. The first is that DoD's share of federal basic and applied research has fallen rapidly, from about one-seventh of the total to about one-tenth. This contrasts sharply with NIH, whose share has risen from one-quarter to more than one-half of spending. These priorities reflect the nation's interest in health care as well as the boom in biotechnology over the past 15 years. But this trend raises the concern that DoD basic research should not be this far below the other federal departments. Furthermore, the recent trend from 2004 through 2006 is downward, as seen in Figure 2.7.

The apparent decline in overall S&T between 2004 and 2006 is of concern, and if this trend continues, the health of DoD basic and applied research could decline as well.

JASON, a DoD-sponsored group of scientists, is also conducting a study on DoD S&T, but the study has not been released as of the writing of this report.

Figure 2.7
Federal Basic and Applied Research Outlays (constant 2000 dollars), 1990–2006



SOURCE: Galama and Hosek, 2008, p. 66.
RAND *MG1176-2.7*

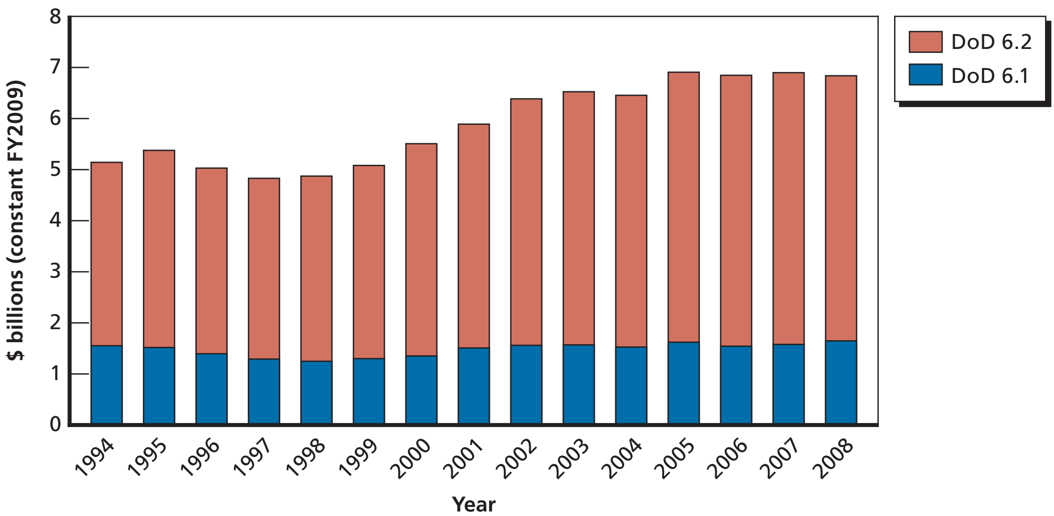
Figure 2.8 focuses on DoD funding for basic research and applied research, Budget Activity 6.1 and 6.2 funding, respectively, in DoD budget parlance. It shows that 6.2 funding expanded after 9/11, growing at a compound annual growth rate of 2.6 percent, but is returning to its pre-9/11 levels. By contrast, 6.1 funding has remained relatively constant since 9/11, after recovering from a downturn in the late 1990s. In fact, the CAGR for basic research spending from 1994 to 2008 is barely half a percent.

Figure 2.9 shows this same funding broken out by service, including defense agencies (primarily the Defense Advanced Research Projects Agency [DARPA] and the Missile Defense Agency [MDA]).

Figure 2.10 shows the trends in Army spending for basic and applied research from 1993 to 2008. Basic research funding has risen from a nadir of $220 million in 1998 and 1999 to $430 million in 2005 before declining in each of the next two years. The CAGR for basic research over the 1993–2008 period was 2.5 percent. Applied research has grown from $580 million in 1996 to $1.3 billion in 2006 before declining somewhat over the next three years. Applied research also grew at a rate of 2.5 percent over the 1993–2008 period.

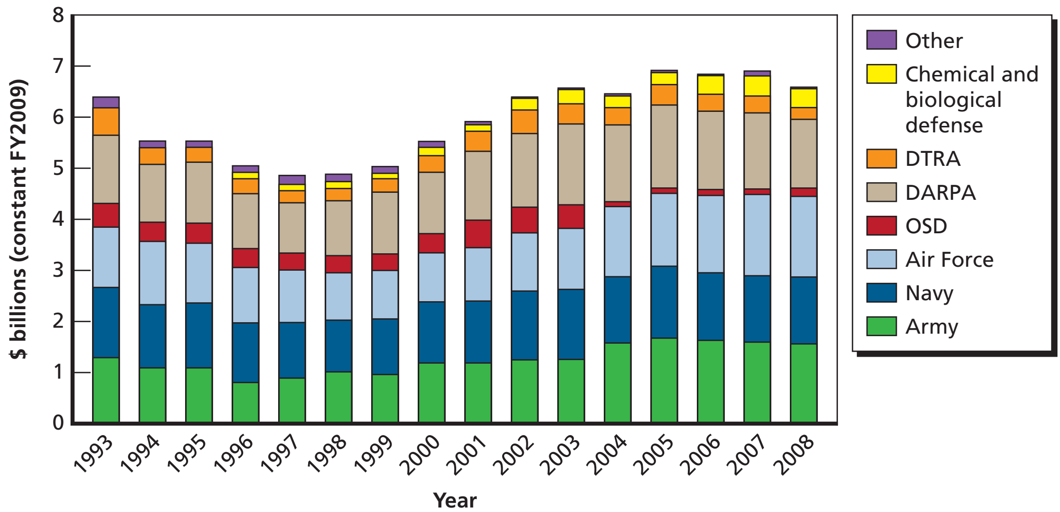
There has been an increase in funding for basic and applied research since the mid-1990s, but that growth has been reversed to some degree in the past few years. The panel is also concerned about the fate of basic and applied research funding beyond FY2009. The financial recession that began in FY2008 could have a downward

Figure 2.8
Trends in Department of Defense Basic and Applied Research Funding, 1994–2008



SOURCE: RAND, based on American Association for the Advancement of Science (AAAS) data (derived from R-1s, the budget explanation documents embedded in DoD budget data books).
RAND *MG1176-2.8*

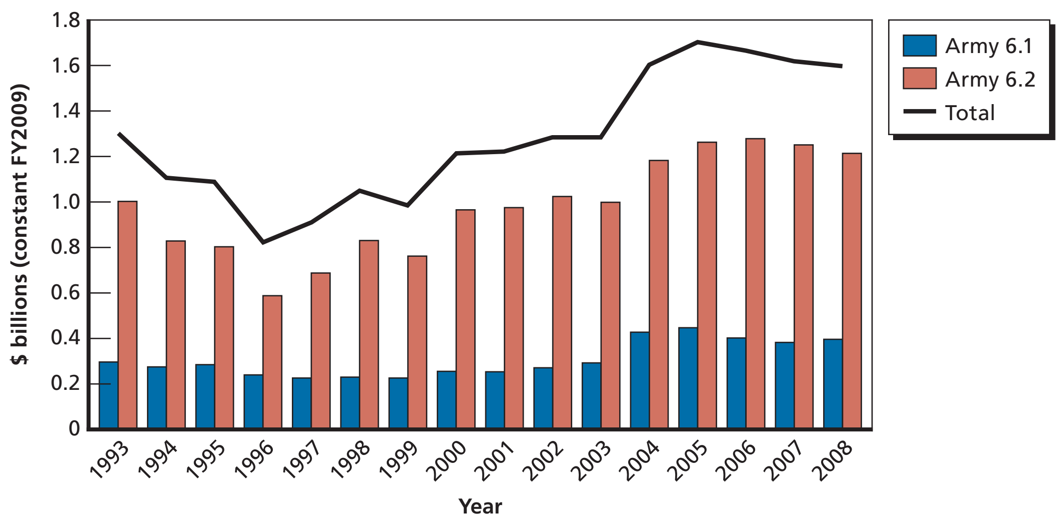
Figure 2.9
Trends in Department of Defense Spending for Basic and Applied Research, 1993–2008



SOURCE: RAND, based on RADIUS (the database of Research and Development in the United States) and R-1 data.

RAND *MG1176-2.9*

Figure 2.10
Trends in Army Basic and Applied Research Spending, 1993–2008



SOURCE: RAND, based on RADIUS and R-1 data.

RAND *MG1176-2.10*

effect on funding of basic research by both private enterprise and the government. The downward trend in 2008 and 2009 is already a signal that there may be further declines in basic and applied research spending by DoD and the Army. If the level of private spending in basic and applied research also declines significantly, a "double whammy" will occur: The Army will not be able to rely significantly on the private sector for basic research, nor will it be able to fill the gap with Army budget funds. The Panel on the Future of Army Laboratories believes this is a serious issue for the Army and for overall defense if it persists for more than a few years, because military operations for the foreseeable future will likely rely on ground forces that must be supported by a continuing and robust S&T base, and an essential component of that S&T base is basic research.

The Obama administration has announced ambitious plans to significantly increase the amount of S&T spending by the federal government, with the goal of reaching 3 percent of GDP, which is higher than the peak of 2.88 percent reached in 1964 (Krame, 2009). If the 3-percent goal is met, it would provide a very strong boost to the prospects for U.S. S&T, but probably not DoD S&T.

The Department of Defense Scientist and Engineer Workforce

Trends in the DoD S&E workforce have been mixed. While the DoD's overall civilian workforce has been on a long downward trend since the end of the Korean War, its S&E workforce has been increasing, both in absolute terms and in terms of the size of the defense budgets (Coffey, 2008, pp. 7–13). But there are some concerns. First, the workforce has not changed its technical profile (S&Es in each discipline) nearly as quickly as the national S&E community, particularly in information technology (IT) fields (Coffey, 2008, pp. 10–11). While IT is, in many ways, a natural area to outsource, the small number of IT professionals in DoD's S&E workforce poses a danger: DoD may lack the information scientists, network system engineers, and information technologists to ensure that its risk is reduced, transition is successful, it remains a smart buyer, and it can envision and benefit from the major breakthroughs occurring in this fast-changing area, which includes network science, secure wireless communications, cyber warfare, and information systems engineering. Second, DoD's S&E workforce is rapidly shrinking as a share of the national S&E workforce (Coffey, 2008, pp. 11–12).

Conclusions

The data presented above indicate that the United States faces some challenges in the years ahead in preserving its strong position in S&T. However, the challenges are probably not as serious as suggested by some of the widely reported studies in

recent years, in part because the influx of foreign S&Es is helping to alleviate possible shortfalls in the job market.

The conclusion of the panel is that these broad trends, while pointing to some challenges for the United States in maintaining a strong position in S&T, are not useful for examining the current state and likely future of Army basic and applied research. This is due, in part, to the fact that much of the available data on U.S. and international S&T spending does not distinguish between basic research, applied research, and technology development, making analysis of trends at the level of basic research impossible. But it is also because much of what determines the quality of basic and applied research within the Army is a function of the research environment within the labs and the resources with which they are endowed.

While these national trends are probably not directly coupled to the Army's ability to conduct high-quality basic and applied research, there are some important ones that bear watching, including the very low number of S&Es being produced in the physical sciences, an area of great importance to the Army and DoD research. A second trend that bears watching is the declining number of U.S.-born S&Es being produced each year. While industry is able to tap into the large pools of U.S and foreign-trained noncitizens, DoD laboratories are not. To the extent that the influx of foreign S&Es can relieve pressure and competition for industry, it can free up U.S. S&Es to work in DoD laboratories. In this case, the critical issue is whether career paths offered by DoD are exciting to graduates.

CHAPTER THREE

The Army Laboratory Enterprise

The structure of the Army R&D enterprise has evolved significantly over the past 20 years in ways that are important for how it funds, conducts, and manages basic and applied research. This chapter describes the Army's current vision and strategy and how and why the current structure evolved. It also examines the funding and demographic trends within the system for their effect on the Army's basic and applied research.

Vision and Strategy

According to the Army's Science and Technology Master Plan (ASTMP), Army S&T exists to provide the knowledge, technology, and advanced concepts to enable the best equipped, trained, and protected Army to successfully execute the national security strategy (Office of the Deputy Assistant Secretary of the Army for Research and Technology, 2007). Essential S&T activities include

- basic research to discover and expand militarily relevant knowledge
- technology invention and innovation
- demonstration of advanced technology capability concepts
- reducing technical risk prior to entering engineering and manufacturing development.

The enterprise that performs these activities includes academia, industry (defense and commercial), federally funded research and development centers (FFRDCs), university-affiliated research centers (UARCs), and government R&D organizations, including those of the Army:

- In addition to S&T performed "in-house," the Army leverages these other communities' investments, talents, inventions, and innovations.
- This engagement of the broader S&T enterprise also helps to avoid technological surprise.

- As work moves from basic research toward technology development and demonstration, more of the effort is contracted with industry, which is essential because industry must have the confidence to competitively bid, design, and manufacture systems and products with proven technology.

Unlike commercial labs, defense industry companies, or even FFRDCs and UARCs, the nation only has one DoD research, development, and acquisition (RDA) system. Our national security depends on its success.

The DoD RDA enterprise is funded and functions differently than academia, industry, and other federal organizations, such as DOE. DoD directives and instructions explain this in more detail. Industry tends to be organized into three broad activities leading to a product: research, product development, and production. Federal agencies such as NASA and DOE perform research and product development, leading to small quantities of systems compared with the DoD RDA system.

DoD research, development, test, and evaluation (RDT&E) appropriations (Budget Activity 6) fund the activities performed by contractors and government organizations that are required for R&D of equipment, material, computer application software, and its test and evaluation (T&E), including initial operational test and evaluation (IOT&E) and live fire test and evaluation (LFT&E). RDT&E also funds the operation of dedicated R&D installation activities for the conduct of R&D programs.[1]

Full-rate production of a DoD weapon system is typically the product of basic research; applied research; advanced technology development; development, test, and evaluation; RDT&E management support; and operational system development activities. Congress prescribes the type of activity that can be performed within each category of these funds, and there is no broad category of research.[2]

DoD S&T consists of the first three activities and a portion of management support. In budget terms, these activities are described as follows:[3]

Basic Research (6.1) is the systematic study directed toward attaining greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind. It includes all scientific study and experimentation directed toward increasing fundamental knowledge and understanding in those fields of the physical, engineering, environmental, and life sciences related to long-term national security needs. It is far-sighted, high-payoff research that provides the basis for technological progress.

Applied Research (6.2) translates promising basic research into solutions for broadly defined military needs and includes studies, investigations, and non-system-

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1 Department of Defense Financial Management Regulation 7000.14-R, Volume 2B, Chapter 5, "Research, Development, Test, and Evaluation Appropriations."

2 Department of Defense Financial Management Regulation 7000.14-R.

3 Department of Defense Financial Management Regulation 7000.14-R and DoDI 3210.1.

specific technology efforts. It may also include design, development, and improvement of prototypes and new processes to meet general mission area requirements.

Advanced Technology Development (6.3) includes development of subsystems and components and efforts to integrate subsystems and components into system prototypes for field experiments and/or tests in a simulated environment. Advanced technology development also includes concept and technology demonstrations (CTDs) of components and subsystems or system models. The models may be form, fit, and function (F3) prototypes or scaled models that serve the same demonstration purpose. Projects typically have a direct relevance to identified military needs. The results of these efforts are proof of technological feasibility and assessment of subsystem and component operability and producibility rather than the development of hardware for service use. Program elements (PEs) funded under this budget activity typically involve pre–Milestone B efforts, such as system concept demonstrations, joint and service-specific experiments, or technology demonstrations. Advanced technology demonstrations (ATDs) are funded with advanced technology development (6.3) funds.

RDT&E Management Support (6.6) includes RDT&E efforts and funds to sustain and/or modernize the installations or operations required for general RDT&E. Test ranges, military construction, maintenance support of laboratories, operation and maintenance of test aircraft and ships, and studies and analyses in support of the RDT&E program are funded in this budget activity. Costs of laboratory personnel, either in-house or contractor-operated, would be assigned to appropriate projects or as a line item in the basic research, applied research, or advanced technology development program areas, as appropriate. Military construction costs directly related to major development programs are included.

Note that the R&D process is not necessarily always a simple linear process, as the numbering would suggest. For example, problems that arise during the phases of applied research or development can require additional basic research to advance knowledge and understanding about a particular phenomenon (Stokes, 1997). This is discussed in Chapter Four.

DoD and Army S&T planning documents provide government organizations and authorized contractors with the DoD and Army S&T vision, strategy, needs, resourced-constrained strategic plan, strategic research objectives, and technology objectives supported by the military customer and laboratory management policy. The 2008 supplement to the ASTMP (Office of the Deputy Assistant Secretary of the Army for Research and Technology, 2008) states the following about S&T strategy:

> The overall Army S&T strategy is to identify, investigate, and mature technology that will enable transformational capabilities for the future force, while seeking opportunities to mature, provide, and facilitate transfer of these enhanced capabilities for the current force.

> The Army's S&T investment strategy is shaped to pursue technologies that create unmatched and unprecedented capabilities for the future land combat forces while leveraging early transitions of these capabilities for the warfighter of today. The S&T program also retains flexibility to be responsive to unforeseen needs identified through current operations. Although the focus of S&T investments is necessarily on the near- and mid-term futures, the Army also funds basic research that seeks to enable the next generation of Soldiers with paradigm-shifting capabilities to dominate in the full spectrum of battlespace environments.

The Army S&T program and priorities are subjected to an extensive array of reviews that are centered around a set of more than 100 Army technology objectives (ATOs), as described in Chapter One of the ASTMP.

> The ATO (Army Technology Objective) portfolio comprises the highest priority Army S&T efforts. They are fully funded efforts and are cosponsored by the S&T developer and the warfighter's representative, the U.S. Army Training and Doctrine Command (TRADOC). Each ATO describes a significant multiyear Army S&T program with well-defined goals, schedule milestones, and quantitative metrics, including technology readiness level (TRL), to assess technology maturity over time. There are three types of ATOs: ATO-Research (ATO-R), ATO-Demonstration (ATO-D), and ATO-Manufacturing technology (ATO-M).

Note that ATOs are not applied to basic research.

> ATO-R programs focus on pursuing individual technologies or components and are usually funded with Budget Activity 6.2 (Applied Research) funds. These are 3- to 5-year efforts that contribute to satisfying warfighter capability gaps or have the potential to achieve significant advancements in technology. An ATO-R "product" is typically a component of a system such as a new type of inertial measurement unit for a missile, an improvement to an existing design such as an infrared focal plane with increased resolution, or an improved tool to meet military needs such as the capability for realistic embedded training. ATO-Rs normally result in a TRL of 4 to 5 ("Component/breadboard validation in laboratory" to "component/breadboard validation in basic relevant environment") and transition to an ATO-D program.
>
> ATO-D programs are intended to transition one or more integrated technology "products" into an acquisition program of record and are usually funded with Budget Activity 6.3 (Advanced Technology Development) funding. These are 2- to 4-year major efforts that mature and demonstrate technology verified by a program executive officer/program manager (PEO/PM), or that demonstrate a major transformational capability endorsed by the Army command or equivalent organization's headquarters. An ATO-D "product" is typically a system, or subsystem model or prototype demonstration in a relevant environment, such as a

> demonstration of new tank cannon munitions or unmanned aerial vehicle sensor payloads. ATO-D program managers are required to have a signed technology transition agreement (TTA) with a PEO/PM no later than 1 year before completion of the program. The TTA specifies the technology products to be delivered, the schedule for delivery, the product maturity at delivery, and the metrics that will be used to demonstrate that maturity. Delivery of technology products demonstrated in an ATO-D should be synchronized with a program of record's schedule. ATO-D programs typically culminate with a TRL 6, although some components may be transitioned at TRL 5.
>
> ATO-M programs address the affordability and/or producibility of an integrated technology solution by developing new or improved manufacturing technologies. A typical ATO-M program is funded with Budget Activity 6.7 (Operational System Development) funds $1 to 3 million annually with a total duration of 3 to 5 years. An ATO-M "product" is typically a demonstration of advanced manufacturing technology and processes, such as the fabrication of improved airframe structures or assembly of high-technology electronic components. Throughout the ATO-M project, there is close coordination between the ATO-M manager, the targeted PEO or PM, the user, and industry to promote successful implementation of enhanced manufacturing approaches. This funding is combined in some instances with ATO-R or ATO-D programs to address the manufacturing and producibility aspects of those programs and improve their transition.

The process by which ATOs are established, adjusted, and implemented is complex and involves many players within the Army's acquisition and operational communities:

> Each year, HQDA [Headquarters, Department of the Army] provides guidance to the S&T materiel development and the TRADOC combat development communities on priorities and needs for annual development of new ATOs or adjustments to ongoing efforts. This guidance is provided jointly by the DASA(R&T) [Deputy Assistant Secretary of the Army for Research and Technology], the Assistant DCS [Deputy Chief of Staff] G-3/5/7, and the DCS G-8, Director, Force Development, and reflects the most current Army planning guidance and modernization strategy, as well as DoD guidance. The resulting ATO proposals are reviewed at Army Command (ACOM) and equivalent Materiel Developer (MATDEV) levels, then at TRADOC Army Capabilities Integration Center (ARCIC), and approved at HQDA.
>
> The ATO development and approval process is depicted in Figure 3 [Office of the Deputy Assistant Secretary of the Army for Research and Technology, 2008, p. 5]. The developing commands' proposals for ATO-Rs are sent to the ARCIC Director for Capabilities Development with recommendations provided to the one-star level HQDA Technical Council (TC). The TC is co-chaired by the HQDA Director for Technology, the HQDA G-8 Director for Joint and Futures, and the TRADOC

ARCIC, Director for Capabilities Development, and includes the directors of the Army RDECs and laboratories.

The ATO-Ds and ATO-Ms are reviewed by the ARCIC Director for Capabilities Development, who provides recommendations to the one-star Warfighter Technical Council (WTC). The WTC is co-chaired by the HQDA Director for Technology, the HQDA G-8 Director for Joint and Futures, and the HQ TRADOC ARCIC Director for Capabilities Development, with SES [Senior Executive Service]-level members from Army laboratories, RDECs, and TRADOC Force Operating Capability leads.

Results of both TD and WTC reviews are provided to the Army S&T Working Group (ASTWG) for approval. The ASTWG is a two-star level group co-chaired by the DASA(R&T) and the DCS G-8, Force Development, with two-star members of HQDA and ACOM equivalent command staffs who have S&T development or oversight responsibilities.

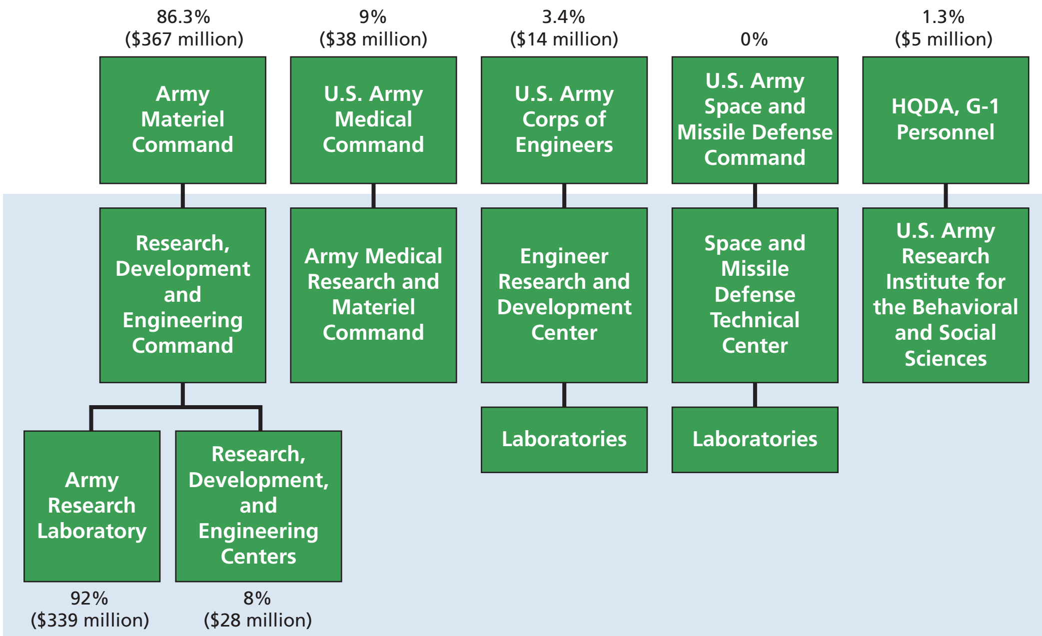
Decisions of the ASTWG are validated annually by the four-star level Army S&T Advisory Group (ASTAG) that is co-chaired by the Assistant Secretary of the Army (Acquisition, Logistics, and Technology) (ASA(ALT)) and the Vice Chief of Staff of the Army (VCSA). Members include the ACOM and equivalent commanders and HQDA principal staff officers responsible for S&T oversight or execution. The results of the annual ATO process are published in the ASTMP and implemented in the Army S&T program.

The Evolution of the Army Laboratory System

The Army laboratory system is a diverse enterprise composed of laboratories, offices, institutes, and centers with different customers and missions. The elements of the system report either to Army Materiel Command (AMC), Army Space and Missile Defense Command (SMDC), Army Medical Command, the U.S. Army Corps of Engineers (USACE), or Total U.S. Army Personnel Command (see Figure 3.1). Because AMC executes more than 80 percent of the Army basic research and a similar percentage of its S&T (6.1 + 6.2 + 6.3) work, this report concentrates on the Research, Development and Engineering Command (RDECOM), which operates under AMC and includes the Army Research Office (ARO), Army Research Laboratory (ARL), and the RDECs (Department of Defense, 2008a).

Following the Defense Management Review of the early 1990s, DoD realigned the S&T executive structure to make it similar to the Defense Acquisition Executive structure established following the Goldwater Nichols Act. The Director, Defense Research and Engineering (DDR&E), was dual-hatted as the Defense S&T Executive. Each of the services followed suit naming their S&T executives. For the Army, the

Figure 3.1
The Army's RDT&E Structure and Share of Total Army Basic Research Funding



SOURCE: Army Research Office, 2009b.
NOTE: Share of funding is based on percentage of Budget Activity 6.1 S&T program executed in the 2009 President's Budget.
RAND *MG1176-3.1*

DASA(R&T) was appointed the Army S&T Executive. In this role, he reported to the Army Acquisition Executive and the DDR&E for Army-wide S&T matters, including vision, strategy, plans, programs, priorities, lab management, and S&E personnel career field. Because Army S&T organizations reside in several different major commands, (e.g., AMC, the Surgeon General, USACE, the Deputy Chief of Staff for Personnel, and SMDC), it is the DASA(R&T)/Army S&T Executive who has policy, strategic planning, prioritization, oversight, and program defense responsibility for Army-wide S&T. Within the Office of the DASA(R&T), it is the Director of Research and Laboratory Management who has the Army basic research and laboratory management portfolio.

ARO, ARL, and the RDECs were significantly consolidated, realigned, and repurposed during the four rounds of base realignment and closures (BRACs) approved by Congress in the early 1990s. The BRAC legislation was passed after the fall of the former Soviet Union in 1989. BRAC sought to close, combine, and/or realign the nation's military bases to the level deemed necessary to support the military's needs into the 21st century. It succeeded in large part because once the BRAC Commission sent its recommendations through the White House, Congress had to vote it up or down

without amendment. Many in government saw it as a rare opportunity to profoundly eliminate unnecessary infrastructure and save billions.

When BRAC commenced, the Army had 42 “laboratories,” and the prevailing sentiment (uniformed military, political appointee, and industry) was that the Army could not afford this infrastructure. Many critics questioned the return that the Army was getting on its investment, the extent of inter-service and inter-lab duplication, and quality of the basic and applied research. OSD was seriously considering consolidating the three services’ S&T activities at OSD under the leadership of the DDR&E, and even considering creating a Defense Research Lab. Some recommended that most of the service labs were beyond reform and that they should be abolished and their mission transferred to the FFRDCs, DOE labs, and/or industry. A Defense Science Board lab study was initiated to look at these issues. A common criticism of the Army lab system was that it was insular, lacked agility, was poorly staffed, and lacked invention, innovation, technology transition successes, and state-of-the-art facilities and equipment. All this took place at a time when American taxpayers were promised a “peace dividend” due to the end of the Cold War.

During the 1991 BRAC cycle, the Secretary of Defense chartered the Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories to review the Army, Navy, and Air Force plans for lab closings and consolidation. The commission concluded that the laboratory system should perform the following functions:[4]

- performing laboratory work—theory, modeling, and experiment
- exploring new concepts and developing new knowledge
- ferreting out new S&T outside the labs
- applying new knowledge to solve enduring Army problems
- conducting developmental testing of new products or processes
- conducting engineering research to aid in scale-up
- facilitating transfer of technology to customers and users
- providing technical advice to Army senior leadership, thereby enabling the Army to be a “smart buyer.”

The “peace dividend” and BRAC and OSD pressures enabled the three military service S&T executives (DASA[R&T], Chief of Naval Research, and the commanding general of the Air Force Research Laboratory [AFRL]) to establish Project Reliance to reduce low-value-added duplication of effort across the services and better understand the role of the services’ labs. For the Army, there were many definitions of what constituted a lab, and it was not possible to defend why all 42 laboratories were needed.

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[4] Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories, 1991.

The Army suffered from too many organizations being reported as "labs" when, in fact, they were a collection of labs, directorates, centers, institutes, and offices, all funded with S&T dollars.

During this time, Wall Street and business schools were increasingly emphasizing near-term, bottom-line financial results, and many companies were abolishing their centralized, or "corporate," laboratories (Anderson and Butler, 2009). The Army's requirement for a centralized laboratory was seriously challenged by many in and out of uniform. ARO relevancy was too often criticized as focused on maintaining strong ties to academia and sponsoring quality university research of questionable value to its customer, the Army. A coherent, affordable strategy and business plan for the lab system, including a clear definition of what a lab is and its essential role, were needed.

After extensive investigation and debate, it was decided that the Army needed an extramural university basic research organization (ARO), a "corporate lab" (ARL), and RDECs (Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories, 1991). These were established (or realigned) and resourced to serve different, essential roles in the acquisition life cycle defined by DoD.[5] Figure 3.2 summarizes some key characteristics of how the AMC enterprise was envisioned to perform RDT&E.

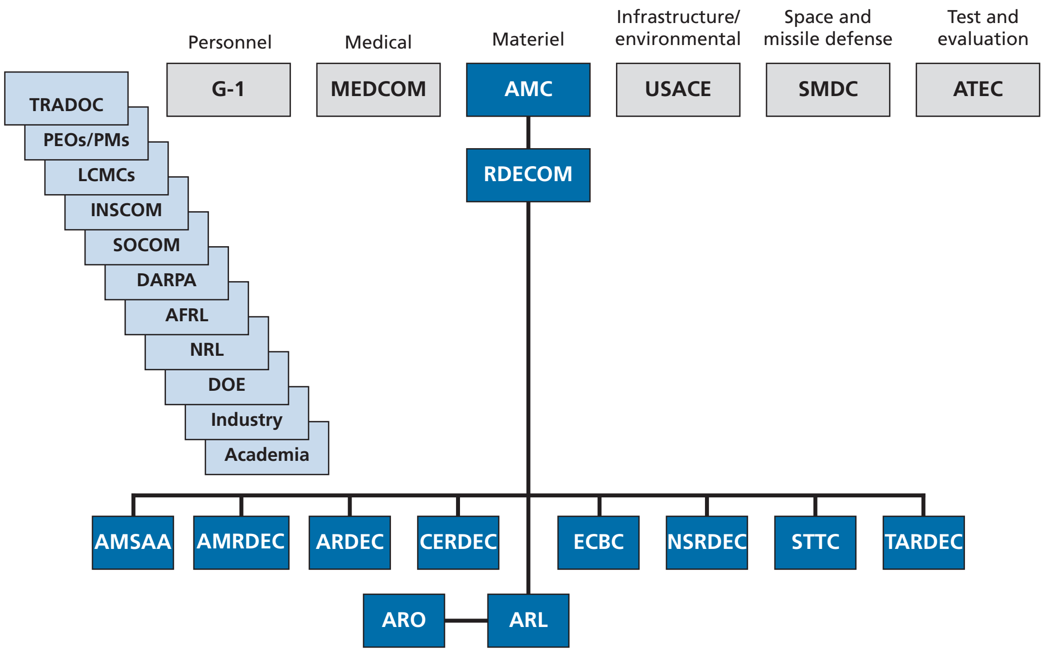
In the wake of this realignment, the purpose, time horizon, focus, funding, staffing, incentives, and business model of each part of the Army lab system are different, but interdependent:

- **The Army Research Office** is mission funded with 6.1 basic research funds.[6] ARO competitively awarded grants sponsor world-class university researchers to perform long-range research relevant to generating the knowledge and technological opportunities that will benefit (preferably uniquely) the Army. These basic research grants are mostly university single-investigator grants. A minor amount of funding was intended for competitively selected university centers of excellence for conducting concentrated, high-payoff research in areas such as nanotechnology, sensing through dense media, and secure mobile wireless communications. Funding for staff, overhead, and the Raleigh, North Carolina, office was to be less than 10 percent of the ARO total funding. Professional staff are almost entirely PhDs, many of whom are former professors, extensively published and with strong networks into professional societies and academia. In addition, the professional staff has ties to universities within the Research Triangle area and

5 See, for example, DoDI 3210.1, DoDI 3201.4, DoDI 3201.01, DoDI 5000.01, DoDI 5000.02, DoDD 5134.3, and DoD 7000.14-R, Department of Defense Financial Management Regulation 7000.14-R, Volume 2B, Chapter 5, "Research, Development, Test, and Evaluation Appropriations."

6 Mission funding is the money in the budget provided directly to a lab to conduct its core mission work. It is also called core funding.

Figure 3.2
Structure of the Army Materiel Command RDA Enterprise



SOURCE: Army Research Office, 2009b.
NOTES: MEDCOM = Army Medical Command; SMDC = Army Space and Missile Defense Command; ATEC = Army Test and Evaluation Command; LCMC = Life Cycle Management Command; INSCOM = Army Intelligence and Security Command; SOCOM = U.S. Special Operations Command; AFRL = Air Force Research Laboratory; AMSAA = Army Materiel Systems Analysis Activity; AMRDEC = Aviation Missile Research, Development and Engineering Center; ARDEC = Armament Research, Development and Engineering Center; CERDEC = Communications-Electronic Research, Development and Engineering Center; ECBC = Edgewood Chemical and Biological Center; NSRDEC = Natick Soldier Research, Development and Engineering Center; STTC = Simulation and Training Technology Center; TARDEC = Tank Automotive Research, Development and Engineering Center.
RAND *MG1176-3.2*

is encouraged to spend a part of their time conducting research in a laboratory. Mostly, ARO hands off its products to ARL.

- **The Army Research Laboratory** is mission funded with 6.1 basic research and 6.2 applied research funding research is mostly performed in-house, with an emphasis on Army-unique problems and associated technologies. The technology transition horizon was to be intermediate term (3–10 years). Although there was to be no 6.3 mission funding, an allowance was made for as much as 30–40 percent of total lab funding to come from customer funds.[7] The intent was to have ARL focus primarily on becoming a world-class "corporate" research lab with

[7] Customers are any organization outside of the lab that are willing to pay it to do work for them. They are typically Army program offices and RDECs, but can also include industry and government organizations outside of the Army, such as DARPA.

more discovery, invention, and innovation relevant to the Army, while encouraging it to earn customer funding to increase relevance to and ties with the customer. ARL was to be a "hands-on," "white coat" basic and applied research lab with state-of-the-art facilities and equipment that would attract the best talent and collaborative efforts with academia and industry through such innovations as the Federated Laboratory Initiative (now the Collaborative Technology Alliance). A collateral benefit envisioned was an improved awareness and leveraging of commercial technology. ARL was not to be everything for everyone. Its primary job was to generate technologies for transition to the RDECs and program managers who are responsible for developing the Army's weapons and support systems. It was thought that by allowing it to compete for customer funds (6.3 and beyond), ARL would earn the support of its customer while still remaining a research lab. Under BRAC, ARL was established by consolidating and realigning seven Army labs, primarily in Adelphi, Maryland, and Aberdeen, Maryland. The ARL Vehicle Technology Directorate was established by realigning the former Aviation RDEC Structures and Materials Directorate at NASA–Langley Research Center and the Aviation RDEC Propulsion Directorate at NASA–Glenn Research Center. New facilities were built at Adelphi and Aberdeen that would not have been possible without the funds that Congress provided to implement BRAC. Adelphi was focused on sensors, microelectronics, information systems, networks, secure wireless communications, and fuzing. Aberdeen was concentrated on advanced armor, materials, mechanics, ballistics, weapons, survivability/vulnerability, robotics, high-performance computing, and human factors/man-machine interface. The National Research Council (2001) and Federal Advisory Commission (1991) present a history and insights into the creation of ARL, respectively. Appendix E summarizes ARL's current mission.

- **Research, development, and engineering centers** are 6.1–6.7 mission funded. S&T is not the majority of their funding; most of what they receive is for applied research (6.2) and advanced technology development (6.3) that is focused on developing and transitioning the technologies to meet the development requirements of their system commands and program executives on schedule and affordably. The RDECs have a more near-term horizon than ARL and are focused on solving known operational problems, technological opportunities, and technical readiness for system development and production. Most of the applied research and advanced technology development funded by the RDECs is performed by industry. Due to their mission and the resulting nature of their effort, they have a higher percentage of engineers and lower percentage of PhDs than ARL. Their only basic research (6.1) mission funding is provided through the In-house Laboratory Independent Research (ILIR) program, similar to the DOE laboratories' Laboratory-Directed Research and Development (LDRD) program. The ILIR program affords the RDEC directors some discretionary basic (6.1) research

funding to quickly seize upon in-house research opportunities that they are in the position to discover and explore with quality, peer reviewed in-house basic research. The RDECs were realigned along mission/product lines—e.g., soldier systems; aviation and missile; tank and armaments; medical; chemical and biological; simulation and training; and communications and electronics (see Figure 3.2). Mostly, the RDECs hand off their products to the developers—PEO/PMs and system commands, who then have industry develop them into systems that can be fielded.

Not all research, be it 6.1, 6.2, or even 6.3 technology demonstrations, will lead to a development program, nor should it. If it does not, the results of the research should be published to build our base of knowledge and allow for other organizations to make use of the results. If S&T activities are focused solely on supporting program development, basic research may suffer, resulting in fewer discoveries, inventions, and innovations; i.e., less investment might be made for explorations that are not clearly destined for specific programs. A case in point are advanced technology demonstrations (ATDs) and advanced/joint concept technology demonstrations (A/JCTDs). Even in the case of A/JCTDs (which are intended to employ proven advanced technologies to demonstrate new, innovative operational concepts) there are three possible outcomes: transition the concept to development, return to the technology base to mature the technologies, or termination. Progressing from 6.1 to 6.3, one would expect, however, the transition rate or yield to improve.

Table 3.1 shows the attributes of each of AMC's RDT&E activities, including the budget for each in 2007 and 2008, and the Panel on the Future of Army Laboratories' assessment of what the different time horizons, endeavors, products, and directives/guidance should be for each. It also shows the panel's assessment of the percentage of research in each category that should be done in-house, that is, within a laboratory or RDEC. Basic research is the endeavor of discovery—the generation of knowledge is its product and it has a far time horizon, such that a fielded system that incorporates the results of basic research could be 15–25 years away. Army basic research is motivated by its potential relevance to the Army. By contrast, applied research is about invention and innovation—technology is its product, and applied research responds to an Army need or opportunity. The time horizon for applies research is somewhat shorter, possibly taking 10–15 years before it is incorporated into a fielded system.

RDA Management

Subsequent to the first four rounds of the BRAC Commission, AMC decided to create a new major command that would subsume ARO, ARL, and the RDECs. All research within AMC is now conducted within RDECOM. The net result is that the director of ARL is two levels below the major command, and the director of ARO is three levels below it.

Table 3.1
Attributes of Different Army Materiel Command RDT&E Activities

Activity	Budget Activity	FY2007 Army[a] ($ billions	FY2008 Army[b] ($ billions)	Horizon (years)	Endeavor	Product	Directive	Execution
Basic research	6.1	0.353	0.373	Far (15–25)	Discovery	Knowledge	Potential relevance to Army	ARO (<10%) ARL (>50%) RDEC ILIR (>90%)
Applied research	6.2	1.189	1.177	Long (10–15)	Invention and innovation	Technology	Army need/ opportunity	ARL (>50%) RDEC (<50%)
Advanced technology development	6.3	1.254	1.319	Mid (5–10)	Innovation and risk reduction	Proof of concept	Army need/ opportunity	ARL (<50%) RDEC (<25%)
Development, test, and evaluation	6.4, 6.5, and 6.7	7.092	8.206	Near (1–5)	Engineering, prototyping, and testing	Production-ready product	Army requirement and specifications	PM (<5%)

[a] President's Budget for Fiscal Year 2009, 2009.

[b] President's Budget for Fiscal Year 2010, 2010.

Technical Workforce

One of the concerns raised by reviews of the Army RDA system in the 1980s and 1990s was the need for the labs to attract quality S&Es and the limitations that the traditional federal civilian personnel system placed on the ability of lab and RDEC directors to do so (Chait, 2009, pp. 2–3).

The DoD acquisition community established the Laboratory Quality Improvement Program (LQIP) in 1993, part of which included the ability to design and implement a streamlined personnel system for civilians (Chait, 2009, pp. 2–6). The Army implemented a new personnel system, called the Laboratory Demonstration Program, at several of its laboratories, including ARL.[8] This program put much more power for managing personnel into the hands of the lab directors. They had flexibility in the salaries they paid new employees, could promote between pay bands without a public competition, could promote senior scientists and technologists without forcing them into management, and could fire nonperforming employees more easily.

According to every past and present lab director that the panel interviewed, this system has been an essential tool for improving the quality of their technical workforce and the ability of their lab to move into new areas as they emerge. However, the Laboratory Demonstration system is still an experiment, not a permanent part of the personnel system, and not in place at every lab and RDEC. Current plans are for the system to be phased out in 2013 when the new National Security Personnel System is phased in at the labs. The National Security Personnel System will eliminate many of the important features of the laboratory demonstration system.[9]

Trends in the Army Laboratory System

The Panel on the Future of Army Laboratories examined a wide range of data to discern trends within the Army lab system, including trends in funding, the technical workforce, and investment in facilities and equipment.

Funding Trends

The total level of Army funding for basic and applied research has grown rapidly, in inflation-adjusted terms, since 1994, after a dip in the late 1990s (see the solid line in Figure 3.3). Note that all costs in the report are expressed in constant (inflation-adjusted) FY2009 dollars. But much of that growth has been in work performed outside of Army laboratories and RDECs—so-called out-of-house work has tripled

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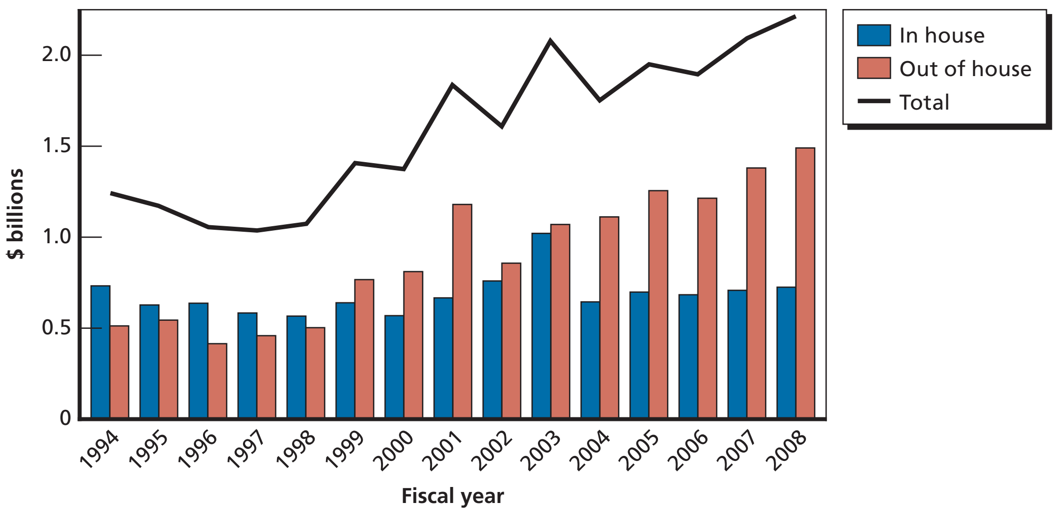
8 The Lab Demo Program is now known as the Personnel Demonstration Project. It is often referred to by either name.

9 A more complete discussion of this issue can be found in Chait, 2009, pp. 5–6.

Figure 3.3
Funding for Army 6.1 and 6.2, by In Versus Out of House, FY1994–2008



SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.3*

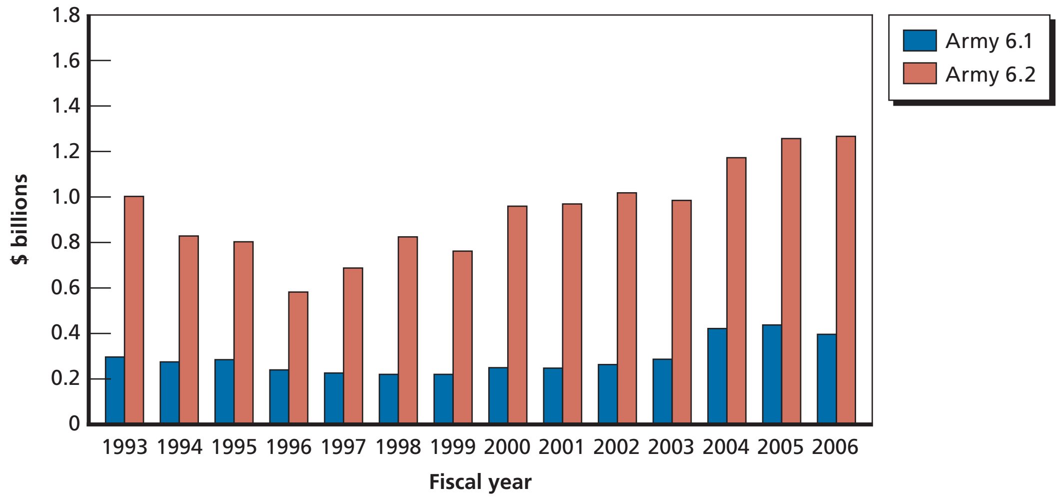
since the 1990s. Meanwhile, spending on 6.1 and 6.2 performed in-house has moved up very gradually; it has just returned in recent years to the 1994 level.

Figure 3.4 shows the inflation-adjusted trends in 6.1 and 6.2 funding separately. Both Army-funded basic and applied research has grown by about 25 percent since 1993. Basic research gets only about one-third the funding as applied research.

The share of the Army's RDT&E budget that is devoted to basic research has been relatively constant since 1993, hovering between 3 and 4 percent (see Figure 3.5). Applied research has been allocated between 10 and 14 percent of Army RDT&E over that period. Figure 3.6 shows how basic and applied research is spent by the different organizations in AMC that spent 6.1 and 6.2 dollars in 2008. ARL and ARO account for almost 90 percent of the basic research funded by the Army in 2008. Applied research work was more evenly distributed, with ARL accounting for only about 40 percent of the total. (ARO gets no 6.2 funding from the Army.)

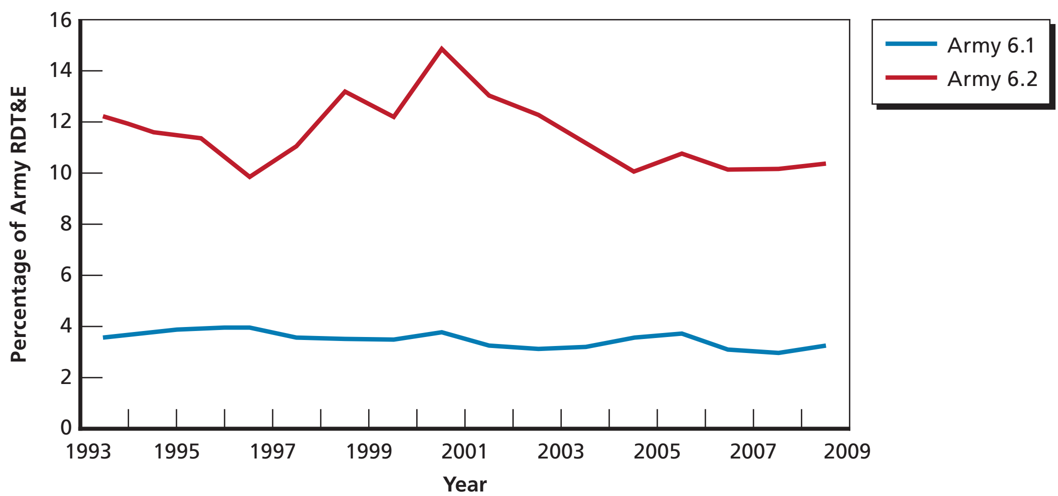
Figure 3.7 shows the breakout of ARO funding by category and is particularly important to the findings of this study. The trend in total ARO funding is positive: It has grown in inflation adjusted terms by almost 80 percent since its post–Cold War nadir in 1994. It has even grown about 30 percent since 1985. However, the core ARO program—investing in the research of single investigators at universities—has declined sharply, dropping 25 percent in the past 15 years and plunging by 50 percent since 1985. This program is being crowded out by university-affiliated research centers

Figure 3.4
Funding for Army 6.1 and 6.2, FY1993–2006



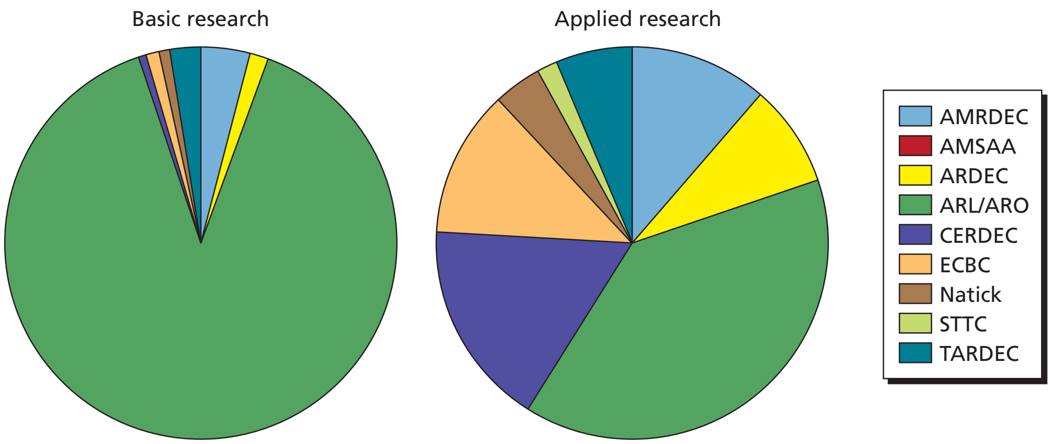
SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.4*

Figure 3.5
Funding for 6.1 and 6.2 as a Share of Army RDT&E Budget, 1993–2009



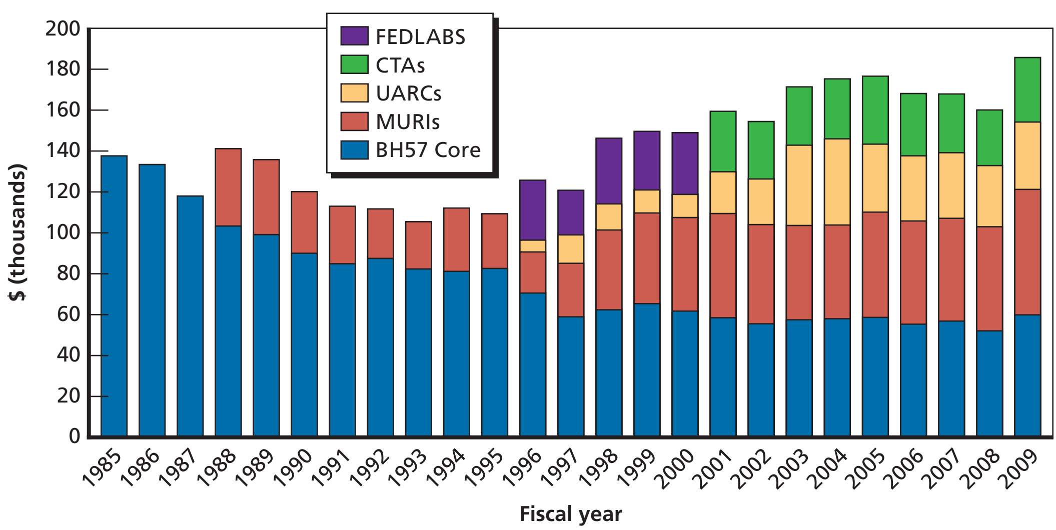
SOURCE: RAND, based on RAND's RADIUS database and R-1 data from the 2007–2010 President's Budget.
RAND *MG1176-3.5*

Figure 3.6
2008 Basic and Applied Research Shares, by Lab and RDEC



SOURCE: Department of Defense, 2008b.
RAND *MG1176-3.6*

Figure 3.7
Army Research Office Funding Breakout by Category, FY1985–2009



SOURCE: Army Research Office, 2009b.
NOTE: FEDLABS = Federal Laboratory Consortium for Technology Transfer. BH57 is the ARO funding element number that provides funds to ARO's core mission of investing with single investigators at universities.
RAND *MG1176-3.7*

(UARCs), multidisciplinary university research initiatives (MURIs), and cooperative technology agreements (CTAs).

Although the discussion so far has focused on the Army, it is useful to compare the Army with other services. The Navy and Air Force each operate a laboratory that focuses on basic and applied research similar to the ARL: the Naval Research Laboratory (NRL) and the AFRL. Unlike ARL, the AFRL is 6.1, 6.2, and 6.3 mission funded. The Navy and Air Force each also has an organization that manages and funds its extramural basic research similar to the Army Research Office. The labs and extramural research funding organizations for each service differ in some aspects and differ in their relationship with their service. For example, the Office of Naval Research actually oversees NRL in addition to managing the Navy's extramural research program, whereas ARO is subsumed under ARL. Chait (2009) presents an excellent discussion of the three service corporate laboratories, including insights into the cultures, keys to past success, and current concerns of the former directors of ARL, NRL, and AFRL.

One of the most interesting comparisons is the difference in funding for in-house basic research between ARL and NRL. Figure 3.8 shows that NRL has consistently received more than twice the resources for in-house basic research than ARL. This is consistent with NRL generally being regarded as the top DoD research laboratory. NRL also does much less funding of outside work in applied research, allowing it to focus more on its mission (see Figure 3.9).

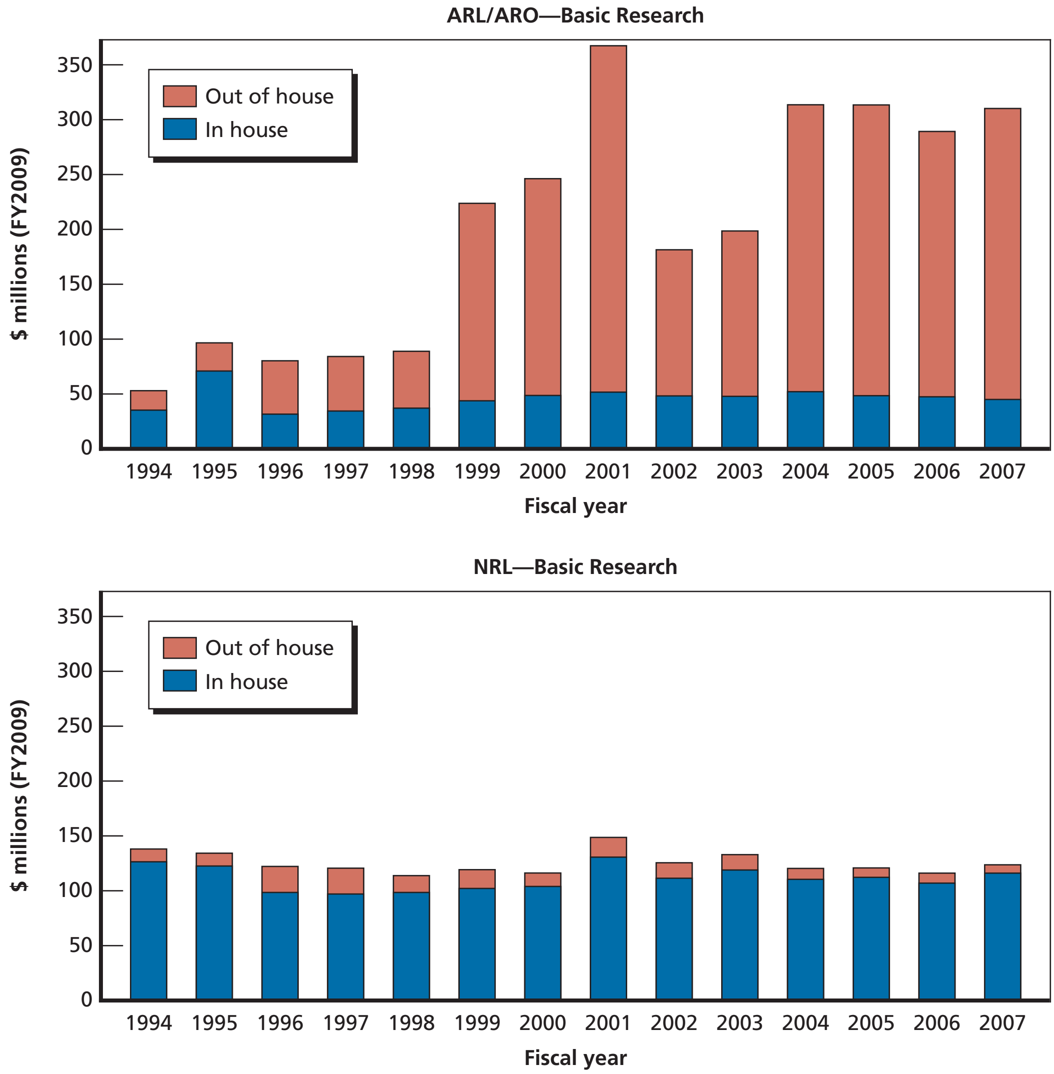
Table 3.2 compares the three service budgets and the budgets of other DoD research organizations for basic research in 2008 by type of program. The Navy spends more on basic research than either of the others, nearly 20 percent more than the Air Force and 40 percent more than the Army.

Workforce Trends

There are a variety of ways to characterize the quality and productivity of the Army's S&E workforce. The DASA(R&T) tracks several categories through the data it collects as part of the Army's Research Laboratory of the Year competition. They include number of new S&Es hired from top schools, papers published and cited, and patents. Many of these categories are reported unevenly or have only been measured for a few years, so they are a few years away from revealing trends.

One interesting measure for which there are data is the percentage of the S&E workforce with PhDs at ARL and the RDECs. ARL is clearly the highest by this measure (see Figure 3.10), as it should be since it is focused on basic and applied research. It has demonstrated strong improvement in this area over the past ten years, rising from 24 percent to just over 35 percent, where it seems to have reached a plateau. Natick Soldier Research, Development and Engineering Center and Edgewood Chemical and Biological Center are in the next group, with PhDs accounting for about 13 percent of

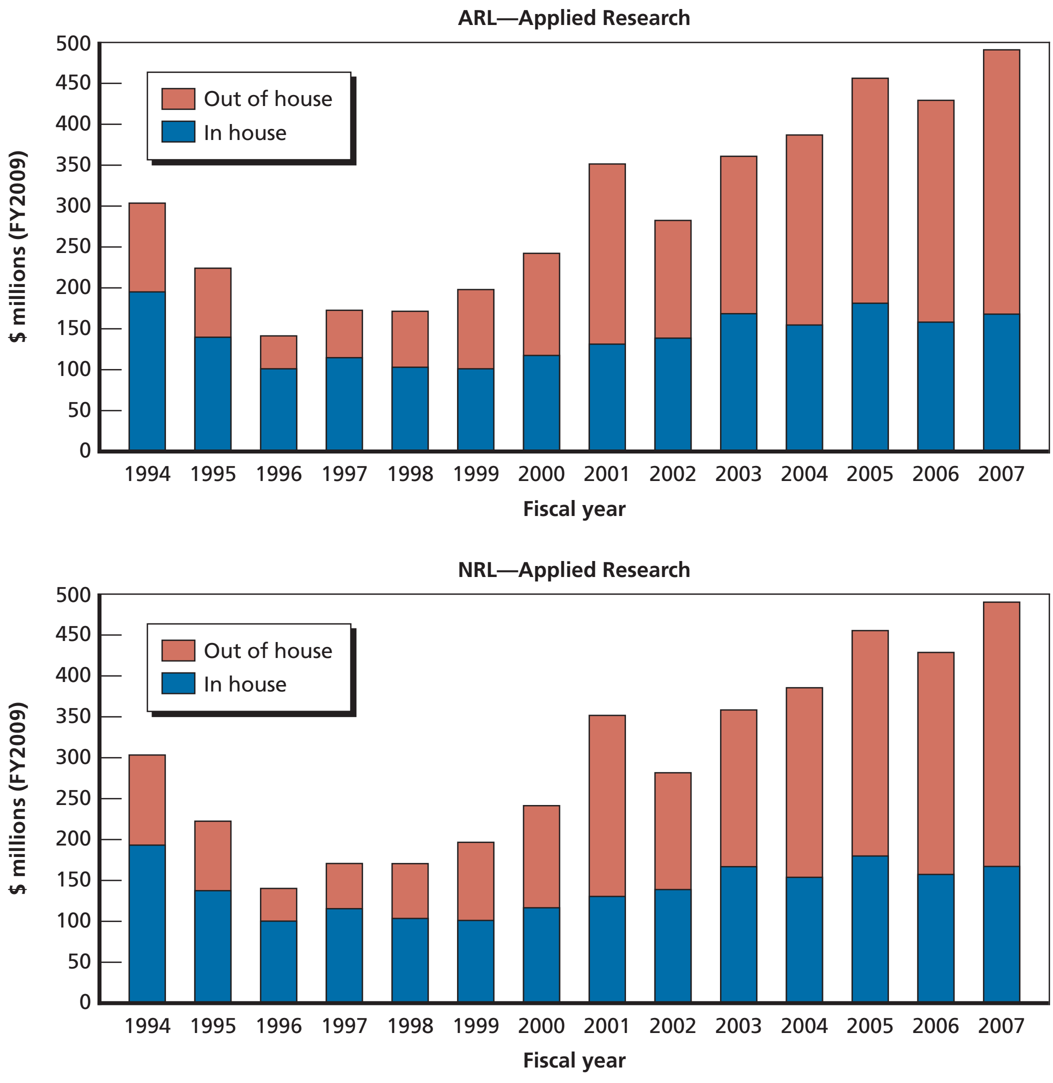
Figure 3.8
Army Research Laboratory and Navy Research Laboratory Basic Research Funding, FY1994–2007



SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.

RAND *MG1176-3.8*

Figure 3.9
Army Research Laboratory and Navy Research Laboratory Applied Research Funding, FY1994–2007



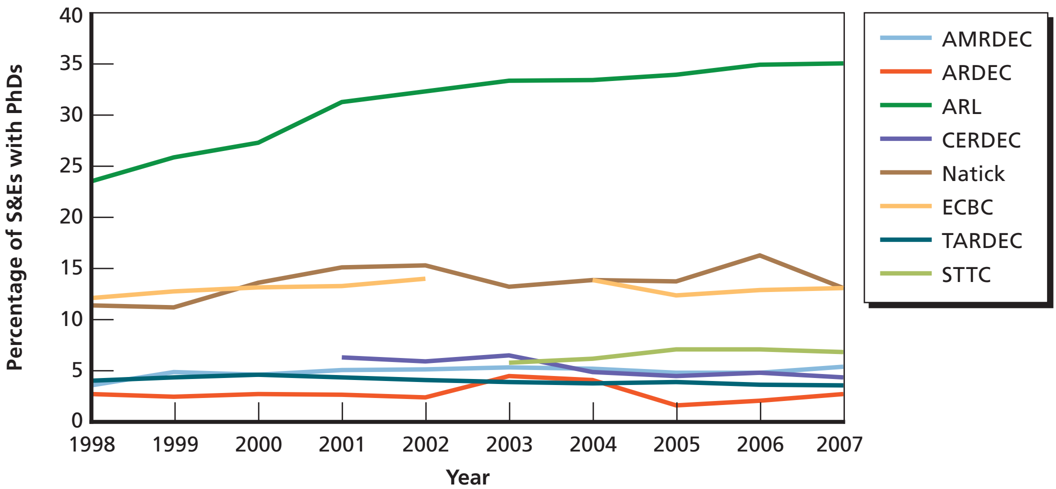
SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.9*

Table 3.2
Breakout of Basic Research Funding by Service and Program Element

Budget Activity	Program Element Number	Program Element Title	President's Budget R-1, February 2008 ($) FY2007	FY2008	FY2009
		DoD Total 6.1	1,524,708	1,633,875	1,695,622
Army					
01	0601101A	In-House Laboratory Independent Research	18,404	21,528	19,832
01	0601102A	Defense Research Sciences	166,403	165,020	176,959
01	0601103A	University Research Initiatives	76,331	82,416	76,980
01	0601104A	University and Industry Research Centers	92,263	110,100	105,622
		Army Total	353,401	379,064	379,393
Navy					
01	0601103N	University Research Initiatives	87,134	98,057	103,707
01	0601152N	In-House Laboratory Independent Research	15,575	16,403	17,298
01	0601153N	Defense Research Sciences	379,581	383,217	407,271
		Navy Total	482,290	497,677	528,276
Air Force					
01	0601102F	Defense Research Sciences	271,481	288,601	309,926
01	0601103F	University Research Initiatives	111,803	119,938	125,949
01	0601108F	High Energy Laser Research Initiatives	12,016	12,556	13,425
		Air Force Total	395,300	421,095	449,300
OSD					
01	0601111D8Z	Government/Industry Co-Sponsorship of University Research	8,679	6,161	
01	0601114D8Z	Defense Experimental Program to Stimulate Competitive Research	8,992	16,931	2,833
01	0601114D8Z	National Defense Education Program	18,425	43,988	68,972
		OSD Total	36,096	67,080	71,805
DARPA					
01	0601101E	Defense Research Sciences	139,521	174,996	195,657
		DARPA Total	139,521	174,996	195,657
Chemical and Biological Defense Program					
01	0601384BP	Chemical and Biological Defense Program	104,830	83,132	53,191
		Chemical and Biological Defense Program Total	104,830	83,132	53,191
Defense Threat Reduction Agency (DTRA)					
01	0601000BR	DTRA University Strategic Partnership Basic Research Program	13,270	10,831	18,000
		DTRA Total	13,270	10,831	18,000

SOURCE: R-1s from President's Budget for Fiscal Year 2008, 2008.

Figure 3.10
Percentage of Science and Engineering Workforce with PhDs at Each Lab and RDEC, 1998–2007



SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.10*

their S&E workforce. The remaining RDECs all hover around 5 percent PhDs, with some as low as 2–3 percent. These numbers have not improved over the past decade.

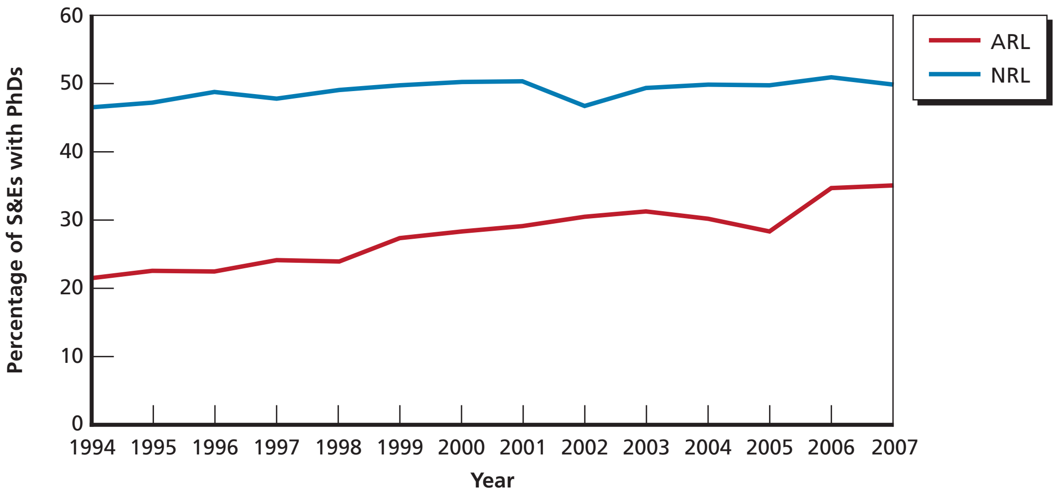
While ARL has by far the highest proportion of PhDs in the Army, it is clearly below the percentage at NRL, which hovers around 50 percent (see Figure 3.11).

Facility and Infrastructure Trends

The Army must spend money to refresh the facilities and equipment at the labs and RDECs. Spending on new capital equipment and S&E equipment is less than $200 million each year and shrinking fast (see Figure 3.12). The data in those figures only go through 2003 because DoD stopped including these data in its annual report. The panel has no reason to believe the funding situation has improved in the intervening years, but the lack of data suggests that these recapitalization issues are not being monitored closely.

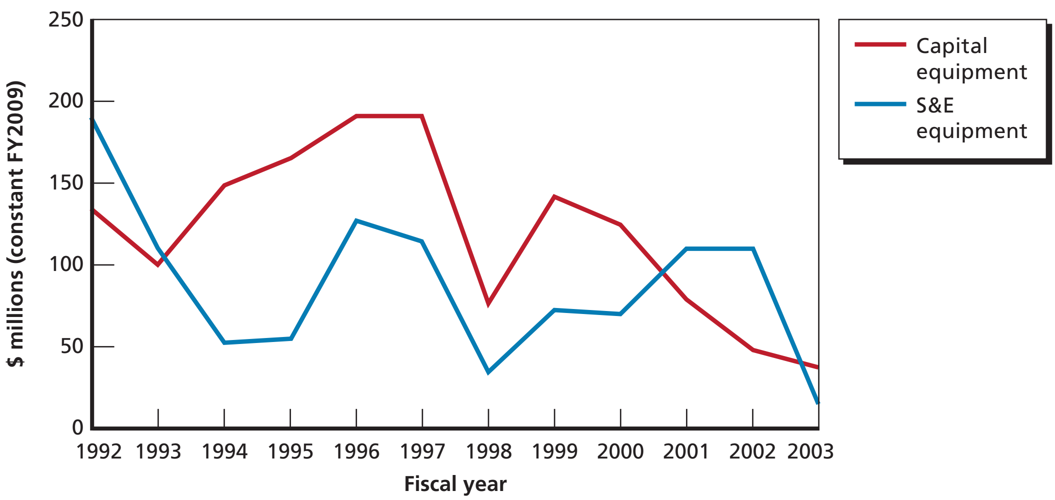
Perhaps the starkest example of the anemic rate of recapitalization is in the Military Construction (MILCON) account. Figure 3.13 shows the spending for ARL from 1994 to 2007 and reveals two things. First, it reflects the sharp spike in 1997 and 1998 due to the BRAC funding for the ARL consolidation. Second, it shows that, other than BRAC funding, MILCON is nearly nonexistent at ARL. The problem is not unique to the Army, however: NRL faces similar challenges in getting MILCON funding, which suggests that service laboratories have difficulty getting funding through the normal MILCON process within DoD and Congress.

Figure 3.11
Comparison of PhD Share of the Science and Engineering Workforce at Army Research Laboratory and Navy Research Laboratory, 1998–2007



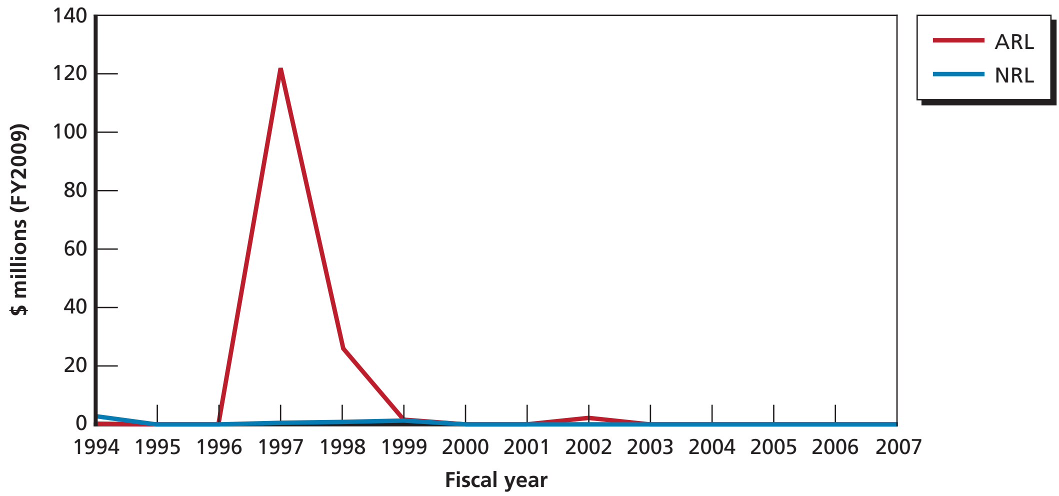
SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.11*

Figure 3.12
New Capital and Science and Engineering Equipment Spending for Army Labs, FY1992–2003



SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2003 and earlier years.
RAND *MG1176-3.12*

Figure 3.13
Military Construction Spending for Army Research Laboratory and Navy Research Laboratory, FY1994–2007



SOURCE: RAND, based on Department of Defense, *Department of Defense In-House Science and Technology Annual Report*, 2008 and earlier years.
RAND *MG1176-3.13*

CHAPTER FOUR

Characteristics of a High-Quality Basic Research Laboratory

The data presented in the previous two chapters provided useful information about trends in S&T and basic research across the United States, DoD, and the Army. But these trends do not get at the issue of what is required to develop and maintain a high-quality basic research laboratory. The Panel on the Future of Army Laboratories examined the characteristics that make such laboratories, based on the literature about these laboratories and the panel members' extensive collective experience running and working in and with high-quality laboratories over the course of their careers. The results of this analysis will be applied to the Army in the next chapter.

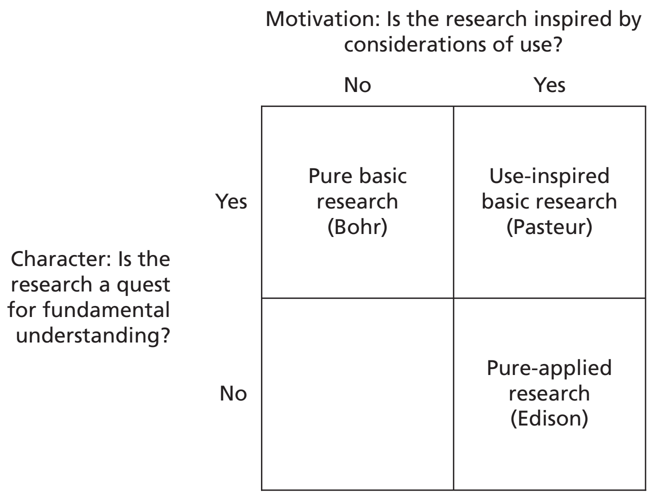
Types of Basic Research

Basic research, as stated in Chapter Three, includes a wide spectrum of activities, ranging from the search for knowledge to innovation and to a seamless transition to applied research.

In many cases it is difficult to appreciate when the research is still basic or when it has transitioned to applied research. The research diagram shown in Figure 4.1 developed by D. E. Stokes is useful to explain the blurring of pure basic, use-inspired basic, and pure applied research (Stokes, 1997).

Stokes divides the world of research into four quadrants defined by what inspires it: whether it is inspired by considerations of use (with an application or a goal to solving a particular problem in mind) or inspired by a quest for fundamental understanding. Figure 4.1 shows two independent axes: the character of scientific research and the motivation of scientific research. The pursuit of fundamental understanding without any regard to application is pure research and typified by Niels Bohr's quest for a model of atomic structure, whereas the pursuit of a solution to a specific problem without regard to achieving fundamental understanding is pure applied research, typified by Thomas Edison's quest to pursue the commercial potential of electric lighting and not deeper understanding. In between is research motivated both by a desire to solve a problem and a quest for understanding. Stokes places Louis Pasteur's work on microbiology into this quadrant because Pasteur was interested both in solving practical problems

Figure 4.1
The Stokes Quadrant Model of Scientific Research



SOURCE: Based on Stokes, 1997.
RAND *MG1176-4.1*

and achieving fundamental understanding of the underlying phenomena. The central message of Stokes's work is that the standard linear model of research, which assumes that basic research leads to applied research, which leads to technology development, which leads to products, does not reflect the way research is actually conducted.

The panel found the Stokes Quadrant Model of Research to be a useful way to approach the issue of Army basic research. One application of the model is to think of the world of research as more of a continuum and not easily separable into three boxes defined by binary answers to Stokes' two questions. In this modified conception, there are degrees to which research is motivated by the desire for fundamental understanding or solving a particular problem. Much of the basic research that the Army conducts is motivated by both a possible application and a quest for knowledge; that is, it falls into Pasteur's quadrant. But some Army research is motivated more by a desire for understanding than solving a problem and starts to fall into the pure basic research quadrant.

At the front end of the basic research spectrum, universities, with their faculty and research teams, usually best provide the search for the most fundamental knowledge, while companies will provide the basic research relevant to their business goals. In the universities, the most likely source of innovative research originates from individual investigator grants. They have the unconventional ideas that may or may not lead to new discoveries. Though universities are usually believed to be the best source of basic research, this may not always be the case. For example, the former Bell

Labs was renowned for its wide range of research and scientists, including having a disproportionately high number of Nobel Prize winners.

The High-Quality Basic Research Laboratory

One definition of a high-quality research organization within the DoD context comes from the 1991 Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories' *Report to the Secretary of Defense*, which states that a high-quality research organization should have the following attributes:

- clear and substantive mission
- critical mass of assigned work
- highly competent and dedicated workforce
- inspired, empowered, highly qualified leadership
- state-of-the-art facilities and equipment
- effective, two-way relationship with the warfighters
- strong foundation in research
- management authority and flexibility
- strong linkage to universities, industry, and other government labs.

This study panel has found a similar set of attributes applies in research organizations in either the public or private sector. The sections below describe each of these attributes and the findings derived from the study of several of the best research laboratories.

Mission of the Corporate Basic Research Laboratory

It is the mission of any basic research laboratory to extend knowledge in areas that may have relevance to the parent organization. Since an organization is spending its resources and has a business plan, the research must have some relevancy to its needs, though the thread may be vague and be rationalized only by educated instinct and expert opinion at the inception. The transition from basic research to application is often a "push and pull" event and sometimes involves several iterations. The basic researcher must be able to envision his or her product's future, promote the product, and persuade the developer how it could be used to address the developer's needs, because the applied scientist may not necessarily have the vision to see the usefulness of some knowledge. The developer has a requirement and seeks solutions. Usually, the basic researcher together with the applied researcher, as a team, can best estimate the relevancy and future applications. But the laboratory must be willing to take risks because the knowledge may not lead to new products and further research. If the

project does not produce usable results after a given number of years, typically three to five years, the work may often be terminated or redirected.

Characteristics of the Researchers

A basic research laboratory is recognized by the quality and quantity of its output, as measured by the breakthrough ideas and inventions it generates, as evidenced by publications, products, patents, and citations of both articles and patents. However, the quality of its personnel (managers and scientists), its leadership, its capital equipment, its facilities, and its mission are the determinants of the output. The quality of the scientists is the foundation upon which the lab is based. Typically, good basic researchers are scientists who are led by curiosity and love to promote their ideas and interact with others in their discipline. But their in-born curiosity leads them to seek continuous updating by attending meetings and conferences. They must be able to publish in the open, peer-reviewed literature to receive recognition and test their results in the broader community. They must have freedom to pursue their interests, but they must be able to sell their activities to and get recognition from management. In some cases, they may wish to move within the lab to see the output of their research lead to the development of new technologies and the production of equipment.

Internal Management Structure of the Laboratory

Managing a basic research organization requires walking a fine line. On one hand, the researcher must be given latitude in selecting what he or she works on; on the other hand, he or she must work in areas that will be beneficial to the organization. Researchers must gain the confidence of their managers in order to receive greater latitude. Management requires having discretionary funding to fund the projects that are the most appealing without requiring an extensive proposal.

Usually, a basic research project must be given three years or more to prove its value. Thus, a source of funding akin to DoD ILIR or the DOE National Laboratories' LDRD is required. The projects can be of different types:

1. Seed projects with large funding (~$1 million) for areas where the laboratory wants to pursue and build a capability. This may include large items of equipment as well.
2. Smaller projects, with one or two primary investiagtors, to fund individual researchers where the researchers have a bright idea they want to pursue.
3. Larger projects with a team of researchers.

The discretionary programs in these labs are typically about 10–15 percent of the total research budget of the laboratory, as evident in the benchmark labs the panel studied. These projects should not be directly related to ongoing research activities funded by the sponsor; rather, they should begin new directions for the laboratory.

The 1983 Packard report on federal research laboratories recommended that "[a]t least 5 percent, and up to 10 percent, of the annual funding of the federal laboratories should be devoted to programs of independent research and development at the laboratory directors' discretion" (*Report of the White House Science Council Federal Laboratory Review Panel*, 1983).

The researcher should not be penalized if the project is not successful, as long as the researcher or research team can show it was quality research, why it was not successful, and how their effort generated knowledge that can help in future work. Basic research organizations must be willing to take risks without penalizing individuals.

Management should also have the expertise to sell and market the research produced by its organization. Successful, relevant basic research should be transitioned into applied research. This should be a responsibility of the management.

Leadership is also an essential part of a top-quality research lab organization. Managers must have a vision of their own and also a deep knowledge of the science, or else they cannot manage and make proper decisions. Also, researchers resent being managed by leaders with inferior knowledge: for example, PhDs will respect managers who are also PhDs and have their own excellent research track record.

Management of the laboratory must be both "top-down" and "bottom-up." The lab director must have a detailed research objective, but the scientists must have the latitude to suggest and propose other areas of inquiry that they believe are of value and should be pursued. Lab leaders must be willing to take risks but also know when to terminate research projects after some reasonable amount of time.

Top-quality laboratories nurture this approach with an active seminar program where they bring in outsiders to give seminars, speak with interested scientists at the institution, and make contacts that might lead to fruitful collaborations. The organization should encourage scientists to publish in the open literature, as long as intellectual property or national security is not threatened. Besides recognition of their scientists, publishing will lead to a wider group of people working to solve the problem in different ways, which can create enormous amount of value for the organization.

The top scientists must be rewarded through both recognition and compensation, without having to move into the management structure to increase their salaries. This is achieved with a two-track promotion scheme whereby the best researchers are rewarded and may end up by becoming fellows of the lab. Fellows' primary responsibilities, besides their research, are to mentor their colleagues, represent the organization's research community externally, and be the voice of researchers to top management. In the benchmark labs with sizable researcher populations, only one or two researchers are appointed as fellows each year, with the ultimate goal being no more than 1 percent of the researchers being fellows at any one time. Compensation, of course, is only part of the key to attracting the best people. Scientists want to be adequately compensated but are arguably more motivated to come to and remain at a laboratory by the

research environment, which includes the caliber of colleagues, quality of facilities, the reputation of the laboratory, and the freedom to pursue interesting work.

External Management of the Laboratory

The ability of a laboratory to do high-quality basic research is also strongly affected by the external environment in which the laboratory must operate. If the organization in which the laboratory operates does not value the output of basic research, pushes research to address only short-term needs, or discourages high-risk work, the quality of the basic research and the reputation of the organization at large will suffer.

High-quality basic research laboratories often report directly to the top management of an organization. This presumes that the top management of the corporation have the long-term vision to appreciate the value of what the research lab can provide them and incorporate that into their business plans. This reporting relationship guarantees the lab protection from the more day-to-day tactical perspective of management from lower divisions and allows them to focus on the strategic objectives to produce breakthroughs. Furthermore, it allows the lab to be measured from a strategic vantage point. The lab's projects can be applicable to any of the organization's divisions. Both Bell Labs and Dupont's Central Research Laboratory in Wilmington, Delaware, report (or reported) directly to their top management. Also, top management controls (or controlled) the bulk of the resources required to operate the laboratory.

Measuring Laboratory Quality and Success

Clearly, high-quality basic research has a significant impact on the Army's technology base and its ability to accomplish its mission. At the same time, ensuring high-quality research requires the use of appropriate metrics to measure quality, which are difficult to specify for basic research. Good basic research is often driven more by scientific than practical, goal-oriented motivations, and its full impact may not be evident for many years.

With the Army's needs in mind, the panel identified metrics that can be used for measuring research quality.[1] These include metrics used by universities, private research laboratories, and peer review and accrediting committees in their assessments of research quality. Furthermore, these metrics are based on the primary activities funded by 6.1 and 6.2 monies by ARL and ARO in the Army's context, namely,

1. basic research
2. applied research
3. technology prototyping and development
4. technology transfer resulting in new or improved products and services.

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[1] For example, see National Research Council, 1993; and Ojanen and Vuola, 2003. Metrics analysis is also augmented by panel experience with practices at private R&D companies such as Bell Labs, Bellcore, Xerox, and others.

This report concentrates mainly on measuring the quality of 6.1 activities, though the output variables also must measure impact of the basic research in activities 1 through 4 in the above list. Each of these can be measured with a varying degree of effectiveness. Metrics can be broken up into two types, depending upon research management objectives:

1. operational monitoring of the research process
2. long-term effectiveness of the research process.

Here, we do not try to separate them out explicitly, but it would be worthwhile for the Army laboratory system to separate them out for the purpose of creating a "dashboard" for day-to-day management of research.

Some of the metrics discussed below work well as far as technology development and transfer activities are concerned, and they provide a way to assess a prospective look at the health of the applied research and, to an extent, at the basic research organization.

The panel considers the research process as a system and divides it into three stages—input, process/environment, and output—in the following model:

Input –> Process/Environment –> Output

One can look at the components of each part of the process and devise metrics for each component, as shown in Table 4.1.

A variety of metrics are available for each quantity to be measured, including the useful metrics included in Table 4.2.

Given the importance of the output measures, some elaboration on these metrics is necessary. An important mechanism for disseminating and validating new knowledge is publication in refereed journals. Unfortunately, this has resulted in the "publish or perish" syndrome, which has led to the creation of publications that few people beyond a close group read. Thus, the full impact of a publication—its contribution to the knowledge base—is difficult to assess without an in-depth understanding of the relevant field. However, a helpful, if imperfect, measure of a publication's impact that

Table 4.1
Basic Research as a System and Its Components

System Stage	Component to Measure
Input	Researchers, research directions, and research management
Process/environment	Research process, environment, facilities and equipment
Output	Effect on scientific endeavor within and outside the laboratory, including creation of next generation basic/applied research, technology transition and contributions to scientific knowledge, impact on users and funders

Table 4.2
Suggested Metrics for Measuring the Performance of a Basic Research System

System Stage		Suggested Metrics
Input	Researcher proficiency and track record	Distribution by S&T degrees, age distribution, and field of research
		Fellowship in professional societies
		Membership in national academies or similar bodies
		Other professional recognition (prizes and awards)
		Breakdown by advanced degrees and scientific and engineering disciplines
		Refresh and turnover rate of staff
		Invited and keynote speeches
	Research directions	Maturity of scientific advancement (How many years the subfield has been in existence?) and emphasis on new emerging subfields
		Need for a major breakthrough in the areas emphasized by the needs of the organization (current results will not scale up, won't work due to changes, etc.)
	Research management	Vision: commonality of goals
		Funding level
		Consistency of funding levels
		Support from funding organization
		Scientific reputation of research managers
		Number of significant breakthroughs and inventions in the past ten years
		Recruitment of high-quality researchers
		Relevance for the enterprise
		Rainmaker: ability to influence sponsors/funders
		Selection process: subfields to invest and proposals. Support for external review of proposals and research.
		Success in helping technology transfer
		Portfolio view of research activities (balance between enhancement, extensions, new challenges in existing areas, new emerging areas).
		Criteria and assessment process for researchers and their career advancement
		Emphasis on peer-reviewed competition for basic research funding

Table 4.2—Continued

System Stage	Suggested Metrics
Research process and environment	Specification of research process, score cards
	Administrative burden on researchers
	Mentoring of new employees
	Operational management (budget, time line, documentation, etc.)
	Intellectual stimulation: seminars, visitors, postdocs, interns
	Unstructured activities: non-project associated time, collegiality, funding for conferences and visitors, travel
	Interaction with customers having real problems, number of collaborations, field trips by researchers to real users
	Portfolio management: support for creation of new areas and cessation of some of the existing areas
	Facility: lab facilities, computing environment
Output	Publications
	Citations of publications by others
	Recognition by peers in terms of new prizes, election to professional society's fellows
	Patents
	Citations of patents by others
	Technology transfer to field
	Long-term impact on users and funders

is widely used in universities is the frequency with which it is cited by peers. Another measure is the recognition by professional peers in terms of awards, prizes, etc., for the work.

Another useful measure of the value of research results is patent activity. The number of patents assigned to Army-supported work would be one indication of the return on Army 6.1 research investments. When good products, processes, algorithms, or other ideas emerge from Army-sponsored research, obtaining patent coverage can also protect their value to the nation. Since the final objective of research is to provide a long-term impact to users and in the theater, it is necessary to track the results of the research's impact in the field and on users. A way to measure the significance of the patent to further invention and innovation is to track the number of times the patent is cited.

Though some of the above metrics are not easy to measure, given that basic research takes a longer-term view, quality research organizations that have been benchmarked

in this report do make serious effort to keep track of these metrics and use them for improving the organization.

One of the Panel on the Future of Army Laboratories' findings (Finding 6 in Chapter Six) is that ARL and the Army laboratory system have not kept a comprehensive list of these metrics and have not used them for improving their research. The panel recommends that a comprehensive effort be mounted to develop and collect such data and analyze a proper set of metrics. Besides helping in governing, these metrics would be useful in articulating the quality and continuous improvement of research in the laboratory system.

Benchmark Laboratories

The previous section described the features of top-quality basic research organizations. This section explores what some specific labs have done to achieve an environment conducive to high-quality basic research: DOE's three nuclear weapon labs and Bell Labs.

The Department of Energy's Laboratories

Comparison of the management and success of basic research in DOE labs with those of the DoD requires acknowledging several differences in guidance and approach. DOE has five multipurpose labs (Brookhaven, Oak Ridge, Argonne, Lawrence Berkeley, and Pacific Northwest National Laboratories) and a single-purpose accelerator lab (Fermilab) that operate under the leadership of the DOE Office of Science (OS) and three labs that operate under the guidance of the National Nuclear Security Administration (NNSA). All these labs have the freedom to operate across what DoD would consider the range of 6.1, 6.2, and 6.3 activities, subject to sponsor approval of a project. However, the definition of basic research programs, selection of performers, and evaluation of results is different between the OS and NNSA labs within DOE.

The DOE Office of Science is the largest funder of basic research in the physical sciences (as opposed to biological/medical research) in the United States. The programs it undertakes (across the range from individual primary-investigator research to the construction and operation of large user facilities, such as particle accelerators, light sources, neutron sources, and supercomputer centers) are almost always defined and prioritized by a widespread national community process that involves both laboratory and academic researchers. Quality of both investigators and the research performance is ensured by competition in peer-reviewed processes similar to those of the NSF and NIH. Since all OS projects are unclassified, there is a wide community that can compete both to define research areas and to receive funding for individual tasks. And since academic collaborators usually have extensive access to all facilities and programs

in the OS labs, there is a wide external community that can comment accurately on individual and group performance. The tendency to perform work in the less expensive academic setting also provides a check on cost and appropriateness of laboratory activities. Additionally, the labs do occasionally perform classified work for multiple government sponsors, particularly the U.S. Department of Homeland Security in recent years.

All DOE labs have the authority to include in their indirect cost structures a component for LDRD, analogous to corporate independent research and development or ILIR within the Army's RDECs. This authority was granted by Congress in the late 1980s and early 1990s in response to the Packard report and allows the laboratories to run a process to self-select projects. As this cost is applied to tasks performed for all agencies at the labs, there has been continual tension with Congress over whether this represents a "diversion" of funds from congressional appropriation and authority. In general, the OS labs have set this number at 2–3 percent of overall funding, feeling that they had access to so large a pool for funds for basic research projects that there was little need to stress this authority. For the NNSA labs, which have much less access to the broader pool of basic research funds from NSF and NIH, as described below, the authority and results are more important.

The three NNSA labs (Los Alamos, Livermore, and Sandia National Laboratories) exist primarily to maintain the U.S. nuclear stockpile and to perform other missions in support of national security, such as selected tasks for DoD, the Intelligence Community, FBI, Department of Homeland Security, etc. To maintain the basic scientific and technical excellence necessary to perform applied tasks for their national security missions, the labs have always performed basic research as well, striving to keep it at about 20 percent of their overall research portfolios. In this sense, the environment for their basic research performance might be best compared to that of the DoD labs. Although the NNSA labs perform the equivalent of 6.1, 6.2, and 6.3 tasks, most basic and applied research funded by the DOE is not conducted in the NNSA labs. Fortunately, the DOE laboratory staffs are able to readily move between research projects funded by OS and those conducted in the NNSA labs.

In the early days of the Cold War (1950s to mid-1970s), the DOE weapons labs were allowed to divert a portion of the classical weapon program block funding to perform basic research in support of the weapon program, calling it "Weapons-Supporting Research." While some of this research was in fact quite good, it was in general not performed under the view or review of the larger technical community, so projects selected were neither broadly vetted nor aligned with the overall national programs, and performance was uneven. As budgetary pressures grew toward the end of the Cold War, the weapon program management reduced such funding at the labs, and those wishing to perform basic research had to seek new funding. There were some notable successes in bringing unique OS programs to the NNSA labs. Among these were the Combustion Research Facility at Sandia California, the Program for Climate

Model Diagnosis and Intercomparison at Lawrence Livermore, and the Neutron Science Center at Los Alamos. Nevertheless, OS resisted placing funding in the NNSA labs because of issues of ownership and control, cost, and difficulties with access for foreign citizen researchers resident in the United States or foreign collaborators. Outside agencies (with the notable exception of the NIH) almost always view the NNSA labs as performers of discrete projects or tasks and are sensitive to both costs and having to pass funds through DOE, thus subjecting them to a fee going to DOE, rather than the lab, of typically 3 percent, which is not viewed as value-added.

The largest driver for improvement in both the amount and quality of basic research in the NNSA labs was the introduction of LDRD authority. Unlike the OS labs, the NNSA labs use nearly their full 8 percent authority to generate a pool of funding for innovative research. Depending on fiscal year and the particular lab, this can represent a budget in excess of $100 million annually for discretionary research at each of the three labs. Almost all of the work in LDRD programs is done inside the laboratories. The pool is annually competed, projects are limited to three-year durations, and clear guidance for the selection is promulgated. In general, each lab allows competition in three roughly equivalent categories: individual primary-investigator projects at the $300,000 level (strongly focused on junior staff development, including postdocs), exploratory research in the disciplines at the $500,000 nominal level, and strategic or directed initiatives at the $1–2 million level, focused on demonstration of new capabilities that could lead rapidly to new programmatic opportunities. For all these levels, there is a strong emphasis on publication in lead journals and the generation of intellectual property. It is also possible to execute a classified LDRD project, though these have been rare.

The project selection process is as important as the results themselves. It combines bottom-up initiative from the individual investigators (and their participation in peer review of individual proposals) and the establishment of top-down strategic guidance for the research areas of interest that makes clear the strategic focus of the laboratories. There is peer review and selection for the smaller projects and more corporate review and selection for the larger projects. Usually a chief technology officer (CTO) or equivalent is responsible for overall management and review of the entire portfolio.

A particular benefit of the review is that the proposers become expert at framing their ideas and defining the value of them. If a proposal idea (typically 200 words) is accepted for review, the primary investigator must explain in writing why the idea is high-risk, how it will be accomplished, and who would care about or act on the result. Verbal defense of the written proposal is required as well. In consequence, the proponents (even unsuccessful ones) become more skilled in the art of grantsmanship and are more successful even outside the LDRD competition. The process is an early identifier of both good ideas and promising individuals.

As is to be expected, there is continuous and useful tension over the distribution of the portfolio among the three levels. The debate over distribution and areas of interest is

intense at each lab every year and occupies an amount of management time appropriate for strategic guidance of this large and valuable resource. Additionally, there is close DOE and NNSA review to assure that the LDRD funds do not directly supplement ongoing programmatic projects or programs of the labs, somewhat analogous to the DoD concern of 6.1 funding being drained for current urgent and applied needs. Another check on quality and relevance of the work is Washington management concern (at middle levels) that the LDRD funds are a drain on vital resources needed for the applied programs. Regular, and somewhat adversarially intended, reviews using outside organizations have repeatedly concluded that DOE gets very high-quality basic research for this investment and that it leads to contributions to the applied programs and to new program capabilities.

Finally, there is the compelling metric of intellectual payoff. As an example, at Lawrence Livermore National Laboratory, LDRD-supported research over the past decade has generated about 20 percent of all peer-reviewed publications, 45–50 percent of intellectual property in the form of patents, and more than 20 percent of intellectual property in the form of copyrights (Lawrence Livermore National Laboratory, 2009, pp. 26–27). The Panel on the Future of Army Laboratories recommends that the Army study the NNSA LDRD process and program as a possible model for both operation and evaluation of its basic research activity.

Bell Laboratories

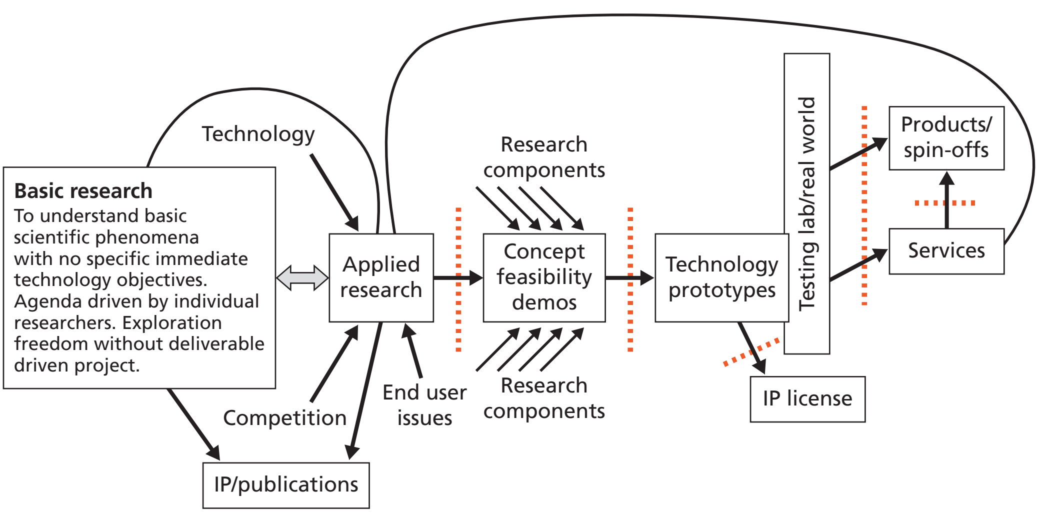
Bell Laboratories provides a paradigm for high-quality basic research in a corporate setting. It was founded in 1925 as the R&D branch of the Bell System. The research performed at Bell Labs was reputed to be the world's best, especially between the 1940s and the 1980s. Over the years, many Bell Labs employees received prestigious awards in their fields, including a number of Nobel Prizes. The number of patents produced was equally impressive. In 2003, Bell Labs received its 30,000th patent (Business Wire, 2003).

Scientists and engineers at Bell Labs developed the techniques and materials for such developments as stereo recording, sound motion pictures, long-distance television transmission, fax transmission, the touchtone phone, the modem, solar cells, cellular telephony, lightwave communication systems, and software that operates, maintains, and manages communication networks everywhere. The laser, the transistor, and the first digital computer based on transistor technology were invented at Bell Labs, as was the Unix operating system. Bell Labs developed the network management and operations systems that support voice and data transmission. In 1962, Bell developed Telstarthe, world's first communications satellite—beating NASA itself to the punch. All of that was the result of research in solid-state physics, materials science, computing science, the behavioral sciences, and communications theory. Most homes today have at least 25 products that are based on Bell Labs technologies.

The key to success of Bell Labs was its ability to conceive some of the most groundbreaking ideas, manage them to fruition, and commercialize them in usable products and services. Besides the extremely dedicated applied research and technology development staff, the backbone of this operation was a basic research organization, which recruited some of the most inquisitive minds in the world and gave them complete freedom to explore topics of broad scientific interest without specific directions and encumbrances of time-driven project management. The basic research organization was a centralized organization of around 1,000 people out of 24,000 employees in 1983 (Noll, 2003). The topics in the basic research organization were chosen partly due to potential for big breakthroughs and ultimate use and impact. However, individual researchers had complete freedom to explore and examine them far beyond the initial scope. This resulted in far-reaching findings, such as the first evidence to support the big bang theory, which was discovered while examining radio noise coming from deep space because it affected communications networks.

Figure 4.2 gives a schemata, created by the panel, depicting the way research processes were organized at Bell Labs. Similar models of research processes existed at Bellcore and Xerox. The basic research organization at Bell Labs was responsible for transformative research, while other applied research and technology development groups were responsible for conducting commercially viable research and converting the results into successful product launches. There were intimate interactions between the basic research organization and the rest of Bell Labs regarding problems, challenges,

Figure 4.2
Schemata of Bell Labs Research, 1940s–1980s



NOTES: Dashed line indicates conforming to an exit criterion. Solid curve line indicates feedback loop. IP = intellectual property.
RAND *MG1176-4.2*

etc. However, it was at the discretion of researchers in the basic research area to decide whether to tackle any particular challenge, the scope of the challenge, and the time commitment. There were postdocs, interns and visitors, weekly seminars, conferences, publications, and encouragement to interact with internal and external research organizations, etc.

This was not an environment free of accountability, however. Researchers were accountable for their research. There was a stringent process of evaluation of researchers in the basic research area that emphasized transformative research and its ultimate impact and utility. There was a constant outflow of researchers from the basic research area to the rest of the organization to focus on newer transformative areas and to seed the successful transformative ideas into the rest of the organization. Finally, though there was a great deal of interaction with external researchers and funding for them; the organization assured (by appropriate recruiting, etc.) that there were key researchers within the organization who had deep understanding of the research topics and were able to provide research leadership in those areas.

One of the key reasons for the demise of Bell Labs as a top-quality basic research organization was the breakup of Bell System and increasingly strong emphasis on short-term commercial research at the cost of the basic research (Noll, 2003).

Bell Labs Management

Bell Labs management reported to the CEO of AT&T through a CTO who was the head of Bell Labs. The head of the basic research organization within the laboratory reported directly to the CTO. Besides the managerial responsibilities of CTO, he was to weigh in on every major decision made by the corporation related to technology and to create and represent the technology vision of the company to the internal as well as external world. Thus, it was necessary for this individual to be well versed with the broad swath of research carried out in the labs and to know most of the key researchers. Xerox Corporation had a similar structure.

Though some of the areas of research had access to a substantial amount of external funding, there was a concern that too much external funding could jeopardize the strategic focus of the labs and would put the researchers in position of using the internal funding as a seed funding to obtain external funding, which could distort the focus of the research. Thus, depending upon a number of factors, external funding sources were carefully planned and turned down if inconsistent with the Bell Labs mission.

One of the findings (Findings 9) of the Panel on the Future of Army Laboratories is that ARL must have a rational process for assessing the value of external funding proposals to the laboratory because these may not be consistent with the lab's mission or would divert substantial management and researcher resources without producing results that support the lab's core mission—discovery, invention, and innovation.

Conclusions

Based on the benchmark labs and the panel members' long experiences in research organizations, the panel found that high-quality basic research organizations have the following characteristics:

- high-quality research staff
- high-quality technical management
- a pool of discretionary funding that amounts to 10–15 percent of lab budget
- peer-reviewed competition for use of discretionary research funds
- freedom for researchers to pursue new, high-risk ideas
- rigorous accountability for researchers for the quality of their work
- talented technical leadership with the vision and expertise to encourage high-risk research, give researchers freedom, and terminate projects when necessary
- promotion tracks for technical staff that do not require them to become managers.

The next chapter will explore what steps the Army can take to adopt these characteristics to its basic and applied research programs.

CHAPTER FIVE

Assessment

The earlier chapters presented the trends in national, DoD, and Army basic and applied research and the characteristics of high-quality research laboratories inside and outside of government. The Panel on the Future of Army Laboratories also compared ARL with high-quality research labs to reveal ways that the Army could improve its basic and applied research with an emphasis on discovery and invention. In this chapter, the panel assesses what the implications of these trends are for the Army's research enterprise, today and in the future.

In short, the panel is concerned that ARL and, to some degree, ARO are drifting away from their intended purpose—as established during BRAC—to the detriment of research quality, discovery and invention. There are a variety of reasons for this trend, including the large portion of ARL work that is funded by customers and focused on short-term results; the growing share of core ARL work constrained by ATOs, technology program agreements (TPAs), and, until recently, the focus on the Future Combat System (FCS); and the small amount of discretionary funding that the ARL Director has to fund high-risk basic and applied research. ARO's core program—the engine of much discovery and invention for the Army over the years—is also being crowded out by less flexible and more enduring centers of excellence and other agreements. The panel is also concerned by the absence of planning for a sustainable recapitalization program for laboratory facilities and equipment and the establishment of a steady funding mechanism for recapitalization. Finally, the panel is concerned about the low proportion of PhD scientists and engineers at ARL and the RDECs relative to the best laboratories. This chapter examines each of these issues in detail.

Army Research Office

As explained in Chapter Three, ARO is funded at much lower levels than the Air Force Office of Scientific Research, the Office of Naval Research, and DARPA. The Single Investigator Program (also known as Program Element 0601102A Project BH57) is the core program of the ARO, an essential force in creating Army-relevant scientific discovery and providing the requisite funding for basic research. It has resulted in

several Nobel Prizes (see Appendix B) over the years (Army Research Office, 2009). Unfortunately, the funding for this program after inflation is 25 percent less than it was just 15 years ago and is only half what it was in 1985. While it is noteworthy that Congress, OSD, and Army customers have turned to ARO to execute several centers of excellence and MURIs, this should not be at the expense of ARO's core program, which has been responsible for most of the breakthrough discoveries that ARO has sponsored (see Appendix A for a list of highlights). The panel recommends that the Army guard against MURIs and centers of excellence squeezing out discretionary funding for discovery and invention. ARO program managers should select fields that are relevant to the Army in the far term. The proposals should be peer-reviewed by both Army personnel and academics. ARO managers should be given wide discretion to build their programs and be held accountable for research quality, progress, and relevance. This is the highly successful DOE and Bell Labs model discussed in Chapter Four.

Army Research Laboratory

The trends in ARL budgets and the information gathered from the panel's examination of the Army R&D enterprise raise several concerns about the balance of its basic and applied research portfolios, trends in the workforce, the degree of high-risk research being done, and constraints on management. Comparing ARL with the best research labs provides insights into how to address these concerns. Table 5.1 makes this comparison in several important areas and summarizes actions that the panel recommends in each area for improving basic and applied research. These areas include workforce, portfolio balance, facilities and equipment, research quality, recognition, and leadership.

Portfolio Balance

The S&T strategy and resource-constrained ASTMP (Army Science and Technology Master Plan, 2007, and the Army S&T Master Plan Supplement, 2008) are formulated by the DASA(R&T) in coordination with OSD/JCS, OSA/HQDA, and TRADOC. The DASA(R&T) sets the priorities for the S&T budget and program objective memorandum in collaboration with TRADOC; AMC; USACE; Army Medical Research and Development Command; SMDC; the Army Research Institute; PEOs/PMs; the Assistant Secretary of the Army for Acquisition, Logistics, and Technology; Army Staff, DDR&E; and the Joint Staff. Army S&T investment is guided by opportunity and military need, unlike development programs, which respond to requirement documents approved by HQDA and TRADOC. One must look not just at the S&T resources invested to assess the health of S&T, but also at real output metrics. While the quantity of awards, peer-reviewed papers, patents, technology

Table 5.1
Comparison of ARL (Less ARO) to the Best Research Laboratories

Attribute	Best Research Laboratories	ARL (Less ARO)	Recommended Correction
Horizon	Mid- to long-term balance	Trending to near-mid term	Restore mid- to long-term balance
Portfolio balance	Core research is majority of work	Core basic (6.1) and applied (6.2) research <50% total	Increase core 6.1 + 6.2 to >50% of total lab funding
	Limited customer funding for development	Customer-funded activity >50% of ARL (less ARO) total funds	Reduce customer-funded 6.3 funding to ~1/3 of total annual funding
	Majority of effort performed in-house	Majority of 6.1 and 6.2 performed out-of-house	ARL (less ARO) should perform >50% core and customer work in-house
Management authority	Lab director discretionary funding >10%	Insignificant amount of director discretionary funding	Make >10% of mission funding (6.1 + 6.2) LDRD-like
Research quality	External peer review of research program	Program peer-reviewed by National Academies	Continue
	Competitive peer review for project selection	Uneven	Expand competitive peer review for funding internal projects
	Use of metrics and trends	Uneven metrics and trend data	Adopt use of metrics with database to support trend analysis
	Extensive use of coops, postdocs, and internships	Minimal use of coops and internships; some NRC postdocs	Expanded use of coops, postdocs, and internships
	Support for peer-reviewed publications, patents, and professional fellowships	Spotty support for peer-reviewed publications, patents, and professional fellowships; lack of emphasis	Encourage peer-reviewed publications, patents, and professional society fellowships
Recognition	Quality of research and leadership highly regarded outside laboratory	Reputation does not reflect the high-quality research being done	Make concerted and continuous effort to raise stature of ARL and highlight its value to the Army
Workforce	S&Es >50% PhDs	S&Es ~35% PhDs	Increase S&Es to >50% PhDs
	Hiring, promotion, and termination decisions by local managers	Civil Service system with temporary, partial local hiring	Make permanent LQIP (Lab Demo) and full local hiring of non-ST/SES S&Es
	Pay for performance	Pay banding	Retain pay banding for S&Es
	Resourced and empowered S&E leaders	STs and Fellows lack budget and stature	Budget for ST & Fellow professional activities
			STs report to SES Director
			Clarify ST & Fellow roles and empower

Table 5.1—Continued

Attribute	Best Research Laboratories	ARL (Less ARO)	Recommended Correction
Facilities and equipment	Recapitalization rate for state-of-the-art lab	No strategy or funded plan	Establish a resource recapitalization rate and plan
		Difficulty competing for MILCON funds	Raise lab construction and equipment funding line within Army budget
Leadership	Empowered by reporting to CEO	Director reports to the commanding general of RDECOM	Have the ARL director report to the commanding general of AMC, the Vice Chief of Staff of the Army, or the Army Acquisition Executive
	Established vision that supports organization's mission		Articulate vision for ARL; aspire to eclipse NRL as DoD's premier lab
	Effective recruiting of S&E leadership from outside	Very limited	Require external search to fill SES and ST vacancies; consider Intergovernmental Personnel Act assignments
			Remove acquisition certification requirement for senior S&E applicants

NOTE: NRC = National Research Council; ST = senior scientist

demonstrations completed, ATOs completed, etc., are relevant, in the final analysis they are not the most important—military mission accomplishment is.

The ultimate customer of Army S&T is the soldier. Intermediate customers include the taxpayer (represented by the White House Office of Management and Budget, Congress, and the Planning, Programming, and Budgeting System), OSD/Joint Chiefs of Staff, TRADOC (the warfighter's representative), and the acquisition community (PEOs and PMs). Often, these intermediate customers have different time horizons and risk tolerance and conflicting priorities and guidance for S&T. They all affect the level and stability of S&T funding and support. If these stakeholders and customers are not satisfied with the productivity of the Army S&T investment, budget stability and level of funding suffer.

The soldier and the intermediate customers of the Army S&T enterprise appropriately have a sense of urgency to field better technology and systems. The Army strategic S&T plan, ATOs, ATDs, A/JCTDs, and the review process described in the ASTMP have greatly improved the effectiveness, transparency, defense, and support of the S&T program; however, customers can better appreciate development prototypes and technology demonstrations than basic research. It is the ARL director's responsibility to protect and advocate basic research, supported by a strong advocate in the Office of the Secretary of the Army.

It is neither possible nor advisable to attempt to make basic research investment more prescriptive in pursuit of more customer support. This would inevitably lead

to research being characterized by shorter time horizons and less discovery. A better, proven approach is to garner customer support by demonstrating invention and innovation, developing advanced technology concepts, effectively managing technology transition, and providing quality technical support to the acquisition and warfighting communities. If that is achieved, customers will be inclined to trust the S&T leadership to invest basic research (6.1) funds wisely, as long as it appears that the researcher, laboratories, and leadership are of the highest quality. This is also essential to maintaining a research culture and environment that fosters discovery. This is consistent with the principles for the conduct and support of basic research required by DoDI 3210.1.

ARL-directed funding continues to suffer from a lack of a critical mass and is being squeezed by the growth in the share of the program covered by ATOs, TPAs with RDECs, CTAs, and customer funding. ARL customer funding has grown to more than half of ARL total funding. ATOs and TPAs now account for more than 70 percent of ARL applied research (6.2) funding.[1]

Too much of ARL's core research is now bound by the ATOs and TPAs. These short-investment-horizon projects are not conducive to basic and applied research, activities that emphasize discovery and invention. The experience of successful laboratories described in Chapter Four indicates that short-term focused work such as ATOs and TPAs should comprise no more than 50 percent of the applied research funding for ARL because it draws too much talent and management attention away from the discovery and invention mission of ARL.

The proliferation of ATOs and TPAs makes the study panel concerned that ARL research has become overly prescribed by the planning and review process discussed in Chapter Three. While that process was created to improve the relevance and productivity of Army S&T investment and to garner better customer understanding and stakeholder support, ARL core research has become overconstrained in a way that shortens basic research horizons, engenders risk aversion, and ultimately discourages invention and discovery. Balance needs to be restored.

Management Authority and Flexibility

A high-quality research lab requires an environment in which scientists and research engineers are allowed freedom to question concepts and issues in depth and are given freedom to pursue basic research in those core areas. The extent to which ARL researchers are allowed freedom to pursue activities beyond their explicit time on project is important to discovery, invention, and even risk reduction. Single-investigator and team awards within the lab are important methods for creating this environment. As a benchmark, the free time given to technical personnel to explore areas of their own

[1] Office of the Director for Research and Laboratory Management, Assistant Secretary of the Army for Acquisition, Logistics, and Technology, email to panel dated July 2, 2009, 10:50 a.m.

interest at Google is 20 percent (as advertised by Google in its job ads), and at Xerox and Bellcore it was around 40 percent.[2] At Bell Labs, it varied: For the basic research area, it was 100 percent (around 1,000 people), and for technology areas, it varied and was substantially less (Sondhi, 2006). With this freedom, the researcher must be held accountable, publish, and give lectures on the work. It is also recommended that researchers write about the work as a part of their performance reviews and be evaluated stringently. In a talk at Stanford University, Marissa Mayer, Google's Vice President of Search Products and User Experience, stated that her analysis showed that 50 percent of the new product launches originated from the 20 percent free time.[3]

Lab management should ensure that people are exposed to interesting problems, create new research directions, and deemphasize current directions when appropriate. The number and significance of new areas started and discontinued are useful metrics for assessing the health of a corporate laboratory such as ARL and should be tracked.

The ARL Director has three initiatives affording him some discretion to shape the research portfolio:[4]

- *Director's Research Initiative (DRI):* In December 1993, the Director of ARL established the DRI program. Its purpose is to annually fund and implement bold, high-risk, original research proposals generated by ARL scientists and engineers that benefit the Army but would not typically be supported under traditional funding programs. The creative atmosphere fostered in this exchange leads to the identification of new and emerging operational concepts and technology thrusts for the future. The DRI process is highly competitive, with funding for the program being allocated from the ARL 6.1 (basic) and 6.2 (applied) research mission lines. To be accepted, proposals must be technically sound, consistent with ARL mission areas, and capable of being completed within one or two years. DRI awards are typically about $100,000 each.
- *Quick Reaction Initiatives (QRIs):* QRIs were started in FY2004 to respond to needs identified by the warfighter in the field; to afford ARL an ability to respond by placing a solution into the hands of the soldier quickly; and to provide an opportunity to get direct feedback. QRI proposals need to emphasize the link between ARL and the soldier and show a smooth transition. QRI proposals must meet the following criteria to be considered for funding: (1) will hasten the transition of ARL research to the soldier, (2) will produce a product in one year or

2 Communications with Sid Dalal, former vice president at Xerox Innovation Group and executive director at Bellcore.

3 "MS&E 472 Course: Entrepreneurial Thought Leaders Seminar Series," ETL Seminar Series/Stanford University, May 17, 2006.

4 Office of the Director for Research and Laboratory Management, Assistant Secretary of the Army for Acquisition, Logistics, and Technology, email to panel dated June 29, 2009a, 1:12 p.m.

less, and (3) will cost between $100,000 and $200,000, on average. QRIs may be considered an example of basic research motivated by application, exemplified by the Pasteur quadrant of Stokes's model (see Figure 4.1).

- *Strategic Technology Initiatives (STIs):* ARL's STIs started in FY2007 to help provide cutting-edge research for the next generation of warfighters by promoting creativity and by offering a means for ARL S&Es to pursue visionary research. These initiatives are typically high-risk with the potential for producing radical, game-changing advancements in analysis, technology, and warfighting capabilities. Such research is inherently long-term R&D and interdisciplinary in nature. New STIs are approximately five-year efforts funded by the ARL Director for the first two years for up to $500,000 per year and then integrated into the directorate's mission program and funded for the remaining years. STIs are supported by extramural research collaborations involving direct extramural funding, ARO grants, and Small Business Innovation Research (SBIR)/Small Business Technology Tranfer (STTR) investments, as well as Army-funded centers. Current STIs are in the areas of bioscience, neuroscience, nanoscience, network science, autonomous systems technology, advanced computing, power and energy, and systems of systems analysis.

Funding for these initiatives in FY2009 was $2.5 million for the DRI, $0.8 million for QRIs, and $3.9 million for STIs. Of the total set aside for these initiatives in FY2009, 11.2 percent is 6.1 money, 81.9 percent is 6.2 money, and 6.9 percent is 6.6 money (management support).[5] Together, these discretionary spending categories account for 4 percent of ARL's in-house budget for basic and applied research, which was $174 million in FY2009. This needs to be rebalanced if discovery and invention are to be encouraged, as originally was intended when ARL was created as the Army's corporate research laboratory and was recommended in the 1983 Packard report.

Research Quality and Peer Review

For the past decade, ARL has voluntarily submitted to independent peer review by a special Technology Assessment Board of the NRC, and the RDEC directors are on the ARL Board of Directors (Lyons, Mait, and Schmidt, 2005). This is commendable; however, peer review should be improved across the Army research enterprise, as recommended in a recent study by the National Defense University (Lyons and Chait, 2009). The panel's review of these periodic assessments, with their numerous metrics, indicates that things are improving; however, this study panel is concerned that ARL is becoming more near-term in its research horizon, to the detriment of discovery and invention. In fact, the ARL Technology Assessment Board sounded a similar alarm in

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[5] Office of the Director for Research and Laboratory Management, Assistant Secretary of the Army for Acquisition, Logistics, and Technology, email to panel dated June 29, 2009a, 1:12 p.m.

the 1999–2000 "Assessment of the Army Research Laboratory" when they concluded "ARL needs to have an appropriate balance of long-range and applied work, enough ARL-directed funding to allow it to follow through on critical topics that might otherwise not be investigated" (Army Research Laboratory, 2003).

Recognition

The panel requested that ARL and ARO provide their own description and assessment of their top 20 discoveries over the past 25 years. (The ARO and ARL responses are listed in Appendix A.) The panel did not distinguish between basic and applied research. ARO responded with an impressive set of descriptions and rationale of what its leadership considered ARO's top accomplishments. It seemed apparent that ARO was keeping track of its basic research efforts and evaluating them; thus, ARO was able to provide on short notice the list and evaluations that the panel requested. The 1999–2000 assessment of the ARL Technical Assessment Board supports this conclusion (National Research Council, 2001).

Notwithstanding the ENIAC and World War II proximity fuze legacies of the former Ballistic Research Laboratory and Harry Diamond Laboratory, when prompted to provide similar breakthroughs over the past quarter century, the ARL (minus ARO) list of accomplishments were uneven, tended to be innovations rather than discovery or invention, and some occurred more than 25 years ago. It is not a list that is distinguishing, either in quantity or quality, certainly not at the level of the ENIAC or proximity fuze inventions of earlier eras. It indicates that ARL is neither tracking nor evaluating continuously its research discoveries, inventions, and breakthroughs. It also suggests that ARL could be doing more to boost recognition of its work and researchers, both externally and within the Army. The quality of ARL research has improved steadily since its inception, but this has not translated into a concomitant increase in its stature outside of the Army. This is a critical component for attracting high-quality staff and therefore needs renewed emphasis. It is also essential for demonstrating to the Army the value of ARL work.

Research, Development, and Engineering Centers

The RDECs are charged with the responsibility to reduce technical risk before entering engineering and manufacturing development. They achieve this through applied research, advanced technology development/demonstration, developmental test and evaluation, providing engineering subject-matter experts to the program managers and requirements community, and providing engineering support to the field.

The ILIR program[6] provides the RDECs' only basic research mission funding. In recent years, Army ILIR funding has declined to less than 5 percent of Army 6.1 funding. The Army should fund ILIR at a level that is at least 5 percent of Army basic research funding, as recommended by DDR&E (DoDI 5134.3), and perhaps up to the 10 percent recommend in the Packard report (*Report of the White House Science Council Federal Laboratory Review Panel*, 1983, p. 8). Even more important, the Army should consider transforming the ILIR program to be more like the DOE LDRD approach discussed in Chapter Four, where competition and peer review determine which projects are most worthy of funding.

As with the best research labs, the quality and leadership of the director of an RDEC is key to success. The panel found that strong knowledgeable leadership has led to widely recognized excellence in an RDEC. Outstanding RDECs had outstanding leadership.

Army Scientists and Engineers

The Laboratory Demonstration Program (National Research Council, 2001, p. 9) initiated by the DDR&E (and now known as the Personnel Demonstration Project) gives the lab or RDEC director the management flexibility required to recruit and retain the right technical talent and the agility to seize technical opportunities. This program is vital, not only to the Army, but to all DoD laboratories and RDECs. Unfortunately, the U.S. Office of Personnel Management and the Under Secretary of Defense for Personnel and Readiness are not inclined to continue this program and appear unwilling to recognize that DoD needs a separate personnel system for S&Es in order to attract, develop, and retain the best and brightest in pursuit of our nation's defense. The Panel on the Future of Army Laboratories recommends that the proven aspects of the Personnel Demonstration Project should be instituted at all Army laboratories and RDECs. In addition, full local hiring authority for S&Es should be granted to laboratory directors for all non-SES and ST positions. The planned National Security Personnel System does not include most of these features (Chait, 2009, pp. 4–6) and should not be allowed to replace the Personnel Demonstration Project.

When compared with the best practices of peers (see Chapter Four), the panel finds that the percentage of PhDs in the total S&E workforce in ARL and the AMC RDECs to be significantly below the percentage in top-quality government and industry laboratories. Although ARL has made progress in increasing the percentage of S&Es with PhDs since its establishment, as shown in Figure 3.11, the percentage of ARL S&Es with PhDs seems to have reached a plateau at 35 percent recently, substantially below NRL, Los Alamos, and Lawrence Livermore. With the exception of the Engineer

[6] Funding for ILIR can be found in Program Element 0601101A in the Army's budget.

Research and Development Center (28.1 percent) and the Natick Soldier Research, Development and Engineering Center (13.5 percent), the percentage of PhDs in most RDECs is in the 2–8 percent range (see Figure 3.10). Notwithstanding the engineering nature of the RDECs, the panel expects their population of PhDs to be higher.

There also must be sustained improvement and recognition of S&E quality, recruiting, retention, and culture of merit and quality. To this end, the panel found the need for increased numbers of S&E interns, cooperative student engineers, postdocs, PhDs, STs, Fellows, researcher mobility across budget categories, and training/exchange/collaboration with industry/academia/operational units. A concerted effort is warranted to recruit top scientist and engineering graduates from the nation's premier universities. According to ARL, the time to fill S&E vacant positions is currently averaging 180 days. ARO, ARL, and the RDECs need local hiring authority for S&Es to solve this.

The Army should implement cited ARL, ARO, and RDEC scientific and technical papers and patents as two useful metrics to track the quality and productivity of the Army research investment over time.

The top scientists must be rewarded financially without having to move into the management structure to increase their salaries. This is best achieved with a two-track promotion scheme whereby the best researchers are rewarded and may rise to become STs and/or Fellows of the lab or RDEC. The Army should strengthen and reinvigorate the management and scientific/technical career tracks and communicate the career opportunities to the workforce and gain their and the personnel communities' "buy-in." Also, the more that these scientists can get their salaries funded directly from the laboratory as well as some discretionary funding for research, the larger the contribution these individuals can make to improving the quality of research at the laboratory.

Many of the research leaders the panel interviewed stressed the seriousness of the dwindling number of U.S. citizens pursuing graduate degrees in scientific and especially engineering fields most important to the Army. Army researchers need security clearances and therefore must be U.S. citizens. The Army should seriously consider establishing a scholarship program for U.S. citizens pursuing a PhD in fields of science and engineering most important to the Army. This should cover the educational cost of the competitively selected student and cooperative employment at the lab or RDEC. Of course, the recipient should also incur a term of employment obligation, given the expense incurred by the taxpayer. This program should significantly address the current shortage of S&E PhDs at ARL and the RDECs and help these organizations be more competitive for the best researchers.

Laboratory and RDEC Facilities and Equipment

Quality, state-of-the-art facilities and equipment are major factors in the recruitment and retention of top scientific and engineering talent. Over a decade ago, BRAC funded much-needed modernization of the affected ARL and RDEC facilities and equipment. A sustained means to finance the continuous improvement of laboratory and RDEC facilities and equipment is required. The panel recommends that the Army explore different methods, similar to those employed by the NRL, NASA, and DOE weapons labs. These include, but are not limited to, establishing a working capital fund or a separate Laboratory Construction appropriation similar to MILCON. A long-range business plan for modernizing and equipping the labs and RDECs is needed at ARL and across the Army.

Laboratory Leadership

Laboratory leadership, including the director and at least two levels below the director, has proven to be one of the most important factors in creating and sustaining a high-quality research laboratory. Good leaders are inspirational, accomplished scientists or engineers who provide a clear vision for the laboratory that supports the mission of the laboratory's parent organization with appropriate basic and applied research. This vision provides the blueprint for excellence within the laboratory and a direction and purpose for that research. Similarly, good leaders below the director can guide research within their branches and have the foresight to encourage their researchers to explore new areas with high-risk research. The panel would like to see ARL articulate a vision that includes an aspiration to boost the external reputation of the laboratory and to eclipse NRL as DoD's premier laboratory.

The best labs that the panel examined keep their leadership and research portfolios fresh by recruiting senior leaders from outside of their organization in addition to promoting stars from within their own ranks. The panel is concerned that the Army labs and RDECs rarely recruit from outside for senior positions, including SES and ST positions. This imbalance must be corrected. One part of the solution will require that the Army remove the requirement that senior managers and S&Es come to the job with high levels of DoD acquisition certification. While it may be important for senior managers to have some knowledge of the acquisition process, they do not require it initially. Instead, the requirement serves to severely restrict the pool of external applicants for these jobs.

As was discussed in Chapter Four, in world-class research laboratories, the director reports directly to the top of the organization—the president, CEO, or head of the agency. In the Army, this would be the commanding general of AMC, the Army Acquisition Executive, or the Vice Chief of Staff of the Army. This arrangement

empowers the laboratory director to pursue the broader organization's agenda without interference from the operational elements of the organization, whose interests and horizons are much more short-term. This command relationship is not in place at either ARL or ARO, which are intended to be the Army's corporate lab and agency for funding extramural basic research, respectively. Subsequent to the first four BRACs, AMC created a new RDECOM and subsumed ARO, ARL, and the RDECs into it. The Army should investigate whether organizing ARL and ARO under RDECOM adds sufficient value to justify both this deviation from best practices for research organizations and its cost in terms of funding, talent, and the toll that this additional management layer has on the time horizon, discovery, invention, and agility of ARL and ARO research.

CHAPTER SIX

Findings

The Panel on the Future of Army Laboratories found—based on its analysis described in the preceding chapters; its interviews with several current and former lab directors, research scientists, and policymakers; its comparison with world-class research organizations; and the panel members' collective experience in R&D—the following:

1. The environment for national and DoD research suggests the following:
   a. The United States, through the 20th century and the first few years of the 21st century, has led the world in basic research, but globalization could challenge this lead.
   b. The United States, through the 20th century and the first few years of the 21st century, has led the world in basic research, but globalization could challenge this lead.
   c. Government-sponsored basic research has been critical to U.S. leadership in research, with DoD being a significant contributor.
   d. National defense has relied heavily on both nongovernment basic research and DoD-sponsored research to meet its needs.
   e. A reduction in DoD basic and applied research resources and also in non-government-sponsored basic research is forecast.
   f. Long-term defense capability, particularly in land warfare, will diminish considerably without a healthy basic and applied research effort.
2. Basic research should expand fundamental scientific knowledge that may lead to future warfighting capabilities. The Army needs a high-quality, inquisitive, agile basic research program with a long-term time horizon in part because geo-political futures and the needs of the future Army are uncertain.
3. The S&T domain is a continuum of discovery, knowledge, invention, innovation, technology development and technology demonstration with feedback cycles. It is often not a simple sequential process whereby an idea is started in basic research, migrates to applied research and then transitions to technology demonstration.
4. The AMC basic research program is increasingly too near term in its focus with declining discovery and invention. In particular, the panel does not find

mechanisms that stimulate staff to undertake high-risk but potentially transformational research in areas relevant to the Army.

5. Failure avoidance has grown to the point that research projects are expected to produce a product in addition to providing scientific knowledge. This has created an RDA culture that trends toward conservative risk management at the expense of discovery, invention, innovation and agility.
6. The Army S&T resources (funding, people and facilities and equipment) database does not permit the necessary analysis and insights required by the Army S&T leadership to execute their policy, strategic, planning, oversight, and program defense responsibilities.
7. The metrics and data actually used by ARL for basic and applied research planning or evaluation are not apparent. There is a lack of metrics that allow it to track how the technology it develops is incorporated into new and modified systems. Thus AMC cannot determine the return on its investments over the past 25 years as evidenced by projects that eventually yield products and capabilities that are fielded.
8. The amount of basic and applied research funding available for the ARL Director to invest at his or her discretion, based on his or her local knowledge and capabilities, is far too low—below the 10 percent recommended in Chapter Five and Table 5.1 of this report. The ARL Director's Research, Quick Response, and Strategic Technology Initiatives are only $7 million annually, from a core research budget of $174 million for in-house research in 2009. Approximately 75 percent of ARL's core applied research funding is committed to ATOs and TPAs.
9. The share of the Army's basic research funding allocated to ILIR has been declining since 1997 and has fallen below the 5 percent guidance from OSD and the 5–10 percent goal recommended by the 1983 Packard report.
10. Technical talent and management attention is a finite resource and must be managed accordingly. The panel finds that too much of ARL technical staff time and management attention is devoted to the pursuit of funding from external clients at the expense of leadership of ARL personnel and management of mission-funded basic and applied research. While work on applied research (6.2) and advanced technology development (6.3) projects is a valid sign of connection to the ultimate customer and of understanding of customer needs, the amount of basic research (6.1) must be balanced accordingly and not neglected.
11. The recruiting, selection, career management, and development of S&Es require more attention and innovation if the Army is to attract, retain, and mentor the staff necessary to meet its needs and perform high-quality S&T. The Personnel Demonstration Project, with its innovative provisions tailored to the scientist and engineer, is a demonstrated success at attracting and retaining good staff, reducing the time to fill openings, and permitting the lab to move in new direc-

tions more easily. These features are vital to the quality of research organizations such as ARL and ARO.

12. The Army has not expanded its S&E workforce rapidly enough in the fast changing research area of network and information sciences, where major breakthroughs continue to occur.
13. The percentage of ARL (less ARO) PhDs is far below the 50 percent typically found at first-rate laboratories, such as NRL, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. The panel is also concerned about the low percentage of PhDs in the RDECs, which is only 2–5 percent at several of the RDECs.
14. The quality of research at ARL has steadily improved since its inception. However, the stature and extent of recognition of ARL research within the external research community have not improved commensurately. For example, there are currently no members of the National Academies at ARL. External recognition is important for attracting and retaining quality staff. As such, improving ARL's standing requires significant attention from ARL and Army leadership. It also requires continuous tracking and assessment by research department leaders of the progress on research projects.
15. The list provided by ARL of major inventions during the past 25 years originating from ARL basic and applied research (not including ARO-funded research) was uneven, tended to be innovations rather than discoveries or inventions and dated back beyond the last quarter century. Notable discoveries and inventions are an important output metric for a research organization. ARL's ability to tell its story in and out of government is vital to establishing its reputation, attracting high-quality staff, and demonstrating the value of its basic and applied research to the Army.
16. The ARL has neither metrics, nor an investment/modernization plan, nor a funding line for anticipated facilities and equipment needs. ARL does not know its facilities recapitalization rate. The Army funded modern ARL facilities at Adelphi and Aberdeen, Maryland, through the BRAC process. However, the panel is concerned that investments and facilities are not being sustained at a rate that would make them competitive enough to attract new staff and flexible enough to move to new areas.
17. ARO has been placed organizationally under ARL, which reports to RDECOM, which reports to the commanding general of AMC. This runs directly counter to the arrangements at the best research laboratories within and outside of government, where they report to the CEO or to the CEO through a CTO. The panel observes that, given the long-range nature of research and how ARL has become increasingly near-term in its focus at the expense of discovery and invention, the benefits of placing ARL and ARO under a large intermediate command like RDECOM as opposed to reporting to the commanding general of AMC are not clear.

CHAPTER SEVEN

Recommendations

The Panel on the Future of Army Laboratories has developed, based on the findings outlined in the previous chapter, a number of recommendations that it believes will improve basic and applied research within the Army. (The numbers in brackets indicate the findings that correspond to each recommendation.)

1. The Army should establish a culture of discovery in basic research to encourage risk-taking and pursuit of opportunities with high potential, in part by providing incentives for experienced researchers to take greater risk in new areas of discovery. [2, 4, 8, 9, 10, 14, 16]
2. The Army should improve the quality of its basic and applied research by improving its agility to move into new areas quickly and to encourage and reward risk-taking by the research staff. [2, 3, 4, 15]
3. The Army should diversify basic research portfolio and establish funding stability in order to restore a longer-term perspective for basic research planning. [2, 4, 9]
4. The Army should increase its S&E bench strength in the fast evolving areas of network and information S&T, where the biggest advances are likely to come. Inspired senior scientists and technologists with vision will be essential in research as well as in design, development, and evaluation and deployment of future systems. [12]
5. The Army should keep ILIR funding at or above 5 percent of the Army's 6.1 budget and execute it like the Laboratory-Directed Research and Development (LDRD) program at the DOE weapons labs, excluding taxing customers. [2, 9]
6. The Army should increase the amount of discretionary basic and applied research funding allocated to the director of ARL to 5 to 10 percent of its total basic and applied research budget, as recommended in the Packard report. ARL should not have more than 50 percent of its 6.2 mission funding obligated for TPAs and ATOs. [8, 10, 11]
7. The Army and DoD should institutionalize the Laboratory Demonstration personnel management system and seek direct local hiring authority for S&Es. Lab

managers should leverage this system to improve the quality of their staffing and the personnel flexibility in their organization. [11, 13, 14]

8. ARL should task a panel of distinguished scientists and engineers from outside the Army to identify the top 20 most important research inventions in the past 25 years from ARL (less ARO) and its predecessor organizations. This story should be captured in media suitable for distribution, to raise awareness among the R&D community in academia, industry, and government of the return on investment for ARL. This effort should be updated every five years. [14, 15]
9. The Army should continuously improve S&E quality, recruiting, and retention within a culture of merit via
   a. the vigorous use of internships, coops, post docs, researcher mobility across budget categories, and training, exchange, and collaboration arrangements with industry and academia.
   b. field training with operational units.
   c. mentoring junior and new S&Es.
   d. seeking external recognition of staff by encouraging publications, patents, and professional society fellowships. [11, 12, 14]
10. The Army should develop and fund a Laboratory/RDEC recapitalization plan, including a recapitalization rate goal for each laboratory and RDEC that sustains the capital stock and technical equipment at a level commensurate with world-class research facilities. This is intended to address the challenges of securing sufficient funding for capital equipment and facility construction. [6, 14, 15]
11. The Army-wide S&T resource database needs to be improved to support timely analysis and decisions for sound policy, strategy, planning, and program defense and oversight. [6, 7]
12. The Army should reconsider the reporting chain for ARL and ARO:
   a. The panel recommends that at a minimum ARL should report directly to the commanding general of AMC as do the AMC major subordinate commands.
   b. Given the Army-wide nature of ARO, the panel recommends that ARO either (1) report directly to the Deputy Assistant of the Army for Research and Technology (DASA(R&T)) or (2) remain part of ARL except be under the operational control of the DASA(R&T). There is precedent for the recommended operational control as the ARI is part of the U.S. Army Human Resources Command but under the operational control of the Deputy Chief of Staff, G-1. [4, 8, 9, 14, 17]

APPENDIX A

Top Discoveries over the Past 25 Years Submitted to the Panel[1]

Army Research Laboratory Top Accomplishments/Discoveries

Title: Ultra Lightweight Ballistically Resistant Materials

Timeframe: 1998

Developed ultra-lightweight ballistically resistant materials that can be incorporated into small arms protective gear which weighs 40% less than current materials technology (Ranger Body Armor; approximately 9 lbs. per square foot) and has the ability to defeat .30 caliber armor piercing projectiles. New soldier protection systems will defeat tungsten-core armor piercing threats at almost half the weight. This technology will revolutionize individual soldier protection.

Title: Kinetic Energy Ammunition for Tank Armaments

Timeframe: 1991

Advanced propulsion, penetrator, and sabot technologies were successfully integrated and fielded in a family of cartridges (M829, M829A1, and M829A2) for the MIA1/A2 Main Battle Tank. The M829A1, deemed the "Silver Bullet" in Desert Storm, was developed in an intensive 2 year partnership between the Army Research Laboratory, Armament Research Development and Engineering Center, Program Manager Tank and Medium Caliber Armament System, industry, and the user community. It serves as a model for rapid technology insertion for the Armed Forces. A fourth generation cartridge known as the XM829E3 is currently in development under the guidance of PM-TMAS.

Title: Corrugated Quantum Well Infrared Photodetector (C QWIP)

Timeframe: 1995–present

ARL developed the first highly sensitive and highly affordable long wavelength infrared detectors. Will provide the Army's next generation of affordable, large format, and high performance Focal Plane Array (FPAs) technologies capable of producing

[1] These summaries were submitted by ARO and ARL and are reproduced here verbatim.

large HDTV format FPAs. This advanced state-of-the-art infrared detection technology will improve quantum efficiency, broadband detection and increase the manufacturing volume while reducing the cost. Affordable high resolution, high sensitivity FPAs will bring better imaging technology for situational awareness to the Soldier in tactical and strategic scenarios.

Title: Projectile Fuzes

Timeframe: 1944–present

ARL's involvement with fuzes for projectiles began through its predecessor organization, the Harry Diamond Laboratory (HDL). In the 1940's, HDL developed the proximity fuze which was recognized as one of the three most significant inventions of WWII. Fuze enhancements continued with the radio proximity fuze in the 1970's (used in the Patriot Missile Defense system), a chaff-resistant fuzing concept in the 1980's which helped enable the Patriot to engage short-range ballistic missiles, and the GPS Registration Fuze Program in the 1990's. With the GPS capability, projectile trajectory is compared to the predicted trajectory and corrections computed for subsequent rounds to considerably enhance the accuracy of artillery fire without the use of a forward observer. The GPS technology developed by ARL is also being extended to guided munitions, both artillery and rocket. Each fuze modification significantly contributed to improved accuracy, performance, reliability and effectiveness over a wide range of weapons systems, requiring substantially fewer rounds to defeat a given target. The improvements translate to significant savings in ammunition costs, transportation costs, and other support costs. Referring to fuze GPS technology, Army Chief of Staff GEN Sullivan commented: ". . . we may need only 1/3 as many rounds to defeat a target. This means fewer ammunition plants, fewer ships, fewer trucks, fewer truck drivers, fewer mechanics and more infantrymen, more military police. . . . This is not gimmickry; this is real power."

Title: Ferroelectric Phase Shifters

Timeframe: 1993

A family of low loss ferroelectric materials was developed. These low loss ferroelectrics provide a low-cost (25:1), lightweight (2:1), compact solution (20:1) for phased array antennas, thus enabling many new military and commercial applications. The low loss ferroelectric phase shifters have had a revolutionary impact on the cost, weight, size, and power consumption of phased array and frequency tunable radar systems within DoD. Firefinder was an early beneficiary.

Title: Flexible Displays

Timeframe: 2003–present

Provided flexible display technologies that are lightweight, rugged, low power and reduced volume through low-cost manufacturing technology. Significant accomplish-

ments included delivery of four inch diagonal QVGA (320x240) flexible displays for integration in customer and partner systems and the world's first flexible low-power electrophoretic display in a soldier relevant PDA format for NSRDEC Future Force Warrior, Soldier Flex PDA (SFPDA). This capability will provide the US Army information systems with enhanced system performance for day/night readable applications.

Title: Heterogeneous Element Processor (HEP)

Timeframe: 1980–1985

The HEP was the first commercial large scale scientific parallel computer employing shared resources MIMD (Multiple Instruction Multiple Data) architecture. The development of this computer was funded and directed by ARL (BRL) under contract to Denelcor, Denver Colorado. The MIMD architecture of HEP had parallel processors that ran independent separate programs on each processor (Multiple instructions) each accessing different data (Multiple Data). The HEP served as a parallel processor pioneer providing guidance to computer designers and developers as they sought to advance parallel architectures in supercomputer systems. Today's parallel computers have revolutionized scientific computing permitting the modeling and simulation of physics based phenomena and life sciences such as human genome mapping to an extraordinary level of fidelity. The start of parallel computing can be partly attributed to the pioneering efforts of the HEP.

Title: Barrel Reshaping Initiative

Timeframe: 2004

ARL developed a method for significantly reducing barrel to barrel differences. This method yielded gun barrels that were twenty-times more uniform than in the past. COL Szydloski, TRADOC System Manager (TSM) for the M1 Abrams tank stated "only real dramatic improvement in tank fleet accuracy since the introduction of the M1 Abrams full solution fire control system." Previously barrel reshaping was a trial and error approach that yielded accuracy of ±2mm along the bore axis. Although this is a relatively small tube-to-tube variation in centerlines it is sufficient to be the primary source of tank to tank differences in center of impacts (COIs). The new (classified) barrel reshaping method yielded a variation less than ±0.1mm along the bore axis that reduced the spread in COIs by more than 50%. Insuring precise barrel reshaping required the development of equipment that could rapidly and precisely measure the uniformity of a barrel. This improved method for barrel reshaping will yield increased lethality for the tank fleet along with a reduced logistics footprint.

Title: Robotics

Timeframe: 2001–present

ARL's research in robotics will permit utilization of UGVs in the full spectrum of warfare, from asymmetric to high intensity conflict. The technical challenges are in:

a) perception that is understood by soldiers, b) advanced learning algorithms, c) robust and adaptable UGVs, d) human interaction from not only the control standpoint but also from the teaming view, e) mission related behaviors that give the UGV a large amount of autonomy. ARL has developed: a) perception algorithms and planning algorithms that permit a UGV to operate in a variety of terrains in a safe mode in populated environments, b) planning software infrastructure to enable autonomous navigation and tactical behaviors, c) multi-sensor fusion approaches toward improved perception in dynamic, urban and populated environments, and d) meaningful collaboration by several autonomous UGVs. ARL research in the future will focus on key future opportunities/capabilities in unmanned systems operations that will: a) increase vehicle autonomy in urban and dynamic environments, b) increase UGV situational awareness, c) provide safer operations of UGVs in proximity to pedestrians and vehicles, d) increase robustness in all environments/conditions, and e) make easier and safer robust soldier/robot teaming behaviors. Autonomous navigation systems will reduce the command and control (C2) workload on personnel operating single UGVs and collaborating with multiple UGVs.

Title: Auditory Hazard Assessment Algorithm for the Human (AHAAH)
Timeframe: 1980–present

ARL's predecessor, the Human Engineering Laboratory, developed the Auditory Hazard Assessment Algorithm for the Human (AHAAH)—a mathematical model of the human auditory system that predicts the hazard from any free-field pressure and provides a visual display of the damage process as it is occurring. The model is a powerful design tool that shows the specific parts of the waveform that need to be addressed in machinery and weapon design. This unique model is the only method of assessing noise hazard for the entire range of impulses that are relevant to the Army. Prior to discovery of the capabilities of AHAAH, designers of weapons systems were unnecessarily restricted in the maximum sound pressure level permitted. This unnecessary restriction hampered design of systems capable of providing maximum lethality necessary to maintain U.S. weapons superiority. By using AHAAH to evaluate impulse noise hazard, materiel developers are permitted to develop weapons systems capable of providing significant increase in power while allowing operators to safely use the weapons systems without sustaining permanent hearing loss (threshold shift of 25 dB or more in the 95th percentile human ear) when properly protected by hearing protection devices. The goal is to predict hearing hazard from impulsive noise while minimizing the possibility of hearing loss, but not over-predicting hazard—which limits materiel developer's options.

Title: LOG Anchor Desk (LAD)
Timeframe: 1996

LAD was the first attempt to harness the use of the internet, combined with data distribution, data visualization and decision support tools to enable a common, relevant logistics picture. Integration of existing logistics analysis models with knowledge-based tools provided powerful decision support to leaders and staffs. The LAD workstation consolidates data from multiple sources to provide situation awareness and decision support for key decision makers on the battlefield. The LAD was deployed to more than 20 sites during 1996, primarily in support of Operation Joint Endeavor, where it was utilized for sustainment operations, redeployment planning, and for extensive sustainment cost reduction analyses within EUCOM. It provided the first information age revolutionary change in logistics planning for the Army.

Title: FALCon
Timeframe: 1997

The Forward Area Language Converter (FALCon) provided a user with no foreign language training an ability to convert a foreign language document into an approximate English translation. FALCon scans a printed page, recognizes individual characters, produces a rough English translation, and runs a tailorable keyword search. Users can then identify captured documents that match a profile of keywords defined by analysts for the mission. Documents that pass this relevance filter can be transmitted electronically, along with the translation produced, for further processing by linguists. With FALCon technology, U.S. troops were able to triage captured documents in the field and transmit them to linguists for full translation and analysis.

Army Research Office Top Accomplishments/Discoveries

Title: Supersonic Beam Observations of Semiconductor Clusters
Performer/Institution: Richard Smalley, Rice University
Timeframe: 1985–1991

In 1984, the Army Research Office (ARO) was the only government funding agency to recognize the potential value of a proposal from Professor Richard Smalley at Rice University to study atomic clusters. Professor Smalley has repeatedly acknowledged ARO's singular role in support of his initial concept. The results from that grant were published in a leading scientific journal, Nature, and proposed that a new form of carbon had been discovered that had the configuration of a soccer ball. Twelve years later, in 1996, Professor Smalley, and his colleagues Sir Harold Kroto and Professor Robert Curl, received the Nobel Prize in chemistry for their discovery of this new form of carbon, called fullerene (also known as Buckminsterfullerene and Buckyballs). Fullerenes are small clusters of carbon atoms, the most common of which has the

molecular formula C60, with the configuration of a soccer ball. This seminal discovery has been frequently cited as the birth of modern nanotechnology. Today, there is a whole field of ongoing research built upon this ground-breaking discovery focused on exploring the physical and chemical properties of new forms of carbon, including carbon nanotubes. Carbon nanotubes have already been used as composite fibers in polymers to improve the mechanical, thermal and electrical properties of the bulk material. In the future, it is possible that carbon nanotubes could be used in advanced light-weight armor, new battery technologies, and in advanced electrical circuits.

Title: Scalable Parallel Algorithms

Performers/Institution: Vipin Kumar and George Karypis, University of Minnesota, Army High Performance Computing Center

Timeframe: August 1990–May 2002

Large-scale scientific computations and simulations are performed on modern parallel machines by breaking up a problem (partitioning) and distributing it over the computer processors in order to take full advantage of the sophisticated architecture. To maximize efficiency, it is necessary that this partitioning be performed in such a way that each processor performs the same amount of work (load balancing) and communication between processors is minimized. However, ensuring that such a partitioning is achieved is not straightforward. Under ARO sponsorship of the Army's High Performance Computing Center, researchers at the University of Minnesota developed a load balancing software package named METIS whose algorithms are based on a sub-area of mathematics called graph theory. Essentially, the computer processors are modeled as nodes on a graph and then METIS uses novel approaches to quickly collapse the graph, partition the smaller graph, and then cleverly smooth and refine to construct a partition for the original graph. METIS is roughly 100 times faster than what was currently possible and produces high-quality partitions that not only effectively balance the load among processors, but also reduces communication time between processors by as much as 50 percent. METIS has become the de facto standard for load balancing at a vast majority of supercomputing centers worldwide and is used extensively at a number of defense labs (WES, ARL, NRL, AHPCRC), national research labs (Sandia, Maui, Oak Ridge, Los Alamos), commercial organizations (IBM, Ford Motor Co., Texas Instruments, Boeing, Rockwell), and universities.

Title: Fast Fourier Transform

Performer: John Tukey, Princeton University

Timeframe: 1960–1970

Signal processing has been a challenging problem for scientists and engineers for decades. ARO-sponsored researcher John Tukey (Princeton and AT&T Bell Laboratories) recognized the superior qualities of digital processing as compared to analog and laid the mathematical foundation for the field of modern data analysis. ARO

provided the relevant applications and $50,000 grant to advance this research. Tukey's 1965 paper in Mathematics of Computation introduced the Fast Fourier Transform (FFT) algorithm, which saved considerable time in processing signals of various kinds (acoustic, electronic, image, communication, optic, etc). Tukey was awarded the Wilks Award by the American Statistical Association, U.S. National Medal of Science, and Medal of Honor from the Institute of Electronic and Electrical Engineers for his ground-breaking work. Over the years through continued military research support, Tukey and others improved the efficiency of FFT algorithms and they are now ubiquitous in engineering and science applications, including data compression like jpeg and processing MRI. Time savings is so significant that entirely new application areas were developed, such as tracking for early air defense missiles. Essentially every communication, aircraft, artillery, air defense, radar, target tracking, detection, and computer system uses this transform or its refinements. In addition, this modest ARO investment is the foundation for data compression for storage and communications systems of all digital computers.

Title: Data Fusion in Large Arrays of Microsensors (Sensorweb)

Performers/Institutions: Sanjoy Mitter and Alan Willsky, Massachusetts Institute of Technology; Sanjeev Kulkarni, Princeton; P. R. Kumar, University of Illinois at Urbana-Champaign

Timeframe: 2000–2006

The ARO funded MURI center, "Data Fusion in Large Arrays of Microsensors (Sensorweb)," developed a new network information theory. This theory complements the now classical Shannon channel information theory. The network information theory developed deals with two fundamental questions: (a) how much information can be transported over wireless networks; and (b) what are cooperative strategies between nodes in a network in order to achieve optimal information transport. The results include sharp information-theoretic scaling laws. The research established the optimality of multi-hop operation in some situations and a strategy for coherent multi-stage relaying with interference cancellation in some others. The team developed scaling laws for two related problems, namely, 1) answering the question how many neighbors should each node in a network be connected in order to maintain overall network connectivity and 2) can transport capacity be measured in a new metric bit-meters/second. The MURI team established procedures for tracking sensor management over long time horizons that take into account (1) the expected information gain from a set of sensor measurements, (2) the energy cost of acquiring those measurements and (3) the energy cost of transmitting a probabilistic model of target location between sensors. This research has led to the first tractable implementation of sensor resource planning that considers planning horizons greater than two iterations. Specifically, horizons on the order of 30 to 75 iterations are possible. A constrained optimization

method for target tracking in such scenarios was developed, implemented, and transitioned to Army systems for IED detection.

Title: Characterization of Odorant Receptors
Performer/Institution: Linda Buck, Harvard Medical School and University of Washington
Timeframe: June 1998–May 2003

Dr. Linda Buck's dissection of odorant receptors and the organization of the olfactory system earned her a Nobel Prize in Physiology or Medicine in 2004. During the early 1990's her studies with Dr. Richard Axel led to the discovery of a large gene family encoding ~1000 different odorant receptors; each individual olfactory sensory neuron in the nose was shown to express one receptor. Subsequent research, supported by ARO Single Investigator Awards, led to her seminal discoveries in unraveling the complexities of odor perception; she determined how olfactory information is organized and transmitted to the brain. Dr. Buck showed that the axons protruding from neurons containing the same odorant receptor converge at specific sites in the olfactory bulb creating a stereotyped sensory map. She then examined the neural networking of this information flow to well-defined regions in the brain cortex in which the information generated from specific odorant receptors is ultimately combined into distinct patterns for a given odor. This patterning is thought to provide the basis for an individual's ability to recognize and discriminate between vast numbers of structurally diverse odors. Dr. Buck's research has enabled the Army to exploit the sense of smell for the trace detection of explosives, threat detection, medical diagnostics and environmental monitoring.

Title: Three Dimensional Photonic Crystals
Performers/Institutions: Eli Yablonovitch, Bellcore and UCLA; Elliot Brown, Lincoln Laboratories
Timeframe: 1991–1993

"They said it couldn't be done." By 1990, theorists were claiming that three-dimensional photonic crystals could not be made with a useful band structure. However, Dr. Yablonovich, working at Bellcore at the time, succeeded in developing such a material in 1991. Photonic materials are made by alternating the index of refraction of a material in a regular fashion resulting in a band structure with, in some cases, a forbidden band. At the time it was merely a scientific curiosity and technological impact was not expected. Here ARO recognized an unrealized opportunity. In January of 1992, ARO held a workshop on the application of photonic crystals motivating the concept for a photonic crystal planar microwave antenna. Subsequently, ARO funded Elliot Brown to test the concept. It was a resounding success: nearly 100% of the drive power in the test antenna radiated into free space. Prior to this achievement, planar microwave antennas were only 10% efficient. The photonic crystal approach revolu-

tionized cell phones by allowing compact and often internal antennas that direct the electromagnetic energy into space rather than into the speaker's head.

The technology was also employed for terminal guidance of the Patriot Missile. A related use is the soldier helmet-mounted antenna. Normally, the metal plating would render the signal useless, but a photonic material solves the problem. While the use of photonic crystals proliferated in the microwave, ARO continued to fund the more challenging problem of making photonic crystals that operate in the visible spectrum. The ability to design band-gaps at desired wavelengths further revolutionized the photonics industry, and the benefits are still accruing. Successes led to myriad applications in solid-state optical devices and sensors. DoD and Army applications are widespread, occurring wherever there are antennas, optical fibers, or imaging systems.

Title: Development of Chemical Warfare Agent Sensors
Performers/Institutions: Alan Russell and Keith LeJeune, University of Pittsburgh and ICx-Agentase
Timeframe: 2002–present

The detection of chemical warfare agents (CWA) on surfaces is a critical capability for the warfighter, and the Army Research Office (ARO) supported foundational research that directly led to a new CWA sensor that combines high sensitivity, stability, and ease of use. With ARO support, Professor Alan Russell, University of Pittsburgh, carried out ground-breaking research on the stabilization and incorporation of enzymes into polymeric, sponge-like materials. The ability to stabilize enzymes led to several commercial products, including a colored chemical wipe for the detection of CWAs. The wipe uses a pH balancing coupled enzyme system to maintain the appropriate pH in diverse environments. This sensor has several new capabilities over existing systems, including the detection of nerve agents on surfaces. The technology's key attributes include excellent stability and long (2 to 5 years) shelf life; compatibility with all testing surfaces; high sensitivity to CWAs; excellent resistance to interference from other compounds; resistance to high temperatures; no start-up time (the response is rapid, within seconds); and is intuitive (easy) to use. The sensors have been fielded in Iraq and Afghanistan by the Defense Intelligence Agency and won an Army's Greatest Invention Award for 2003.

Title: Atomic Resolution Magnetic Resonance Imaging
Performers/Institutions: John Sidles and Daniel Rugar, University of Washington and IBM
Timeframe: July 2001–present

For the past decade, ARO has spearheaded the development of magnetic resonance force microscopy (MRFM). This technique achieves incredible levels of sensitivity by coupling the magnetic resonance of atomic species (electron or nuclear spins) to the mechanical resonance of an AFM cantilever. Changes in the resonance of the latter

can be monitored to very high levels of precision. In 2004, under the leadership of Dan Rugar at IBM-Almaden, the experimental effort achieved a significant milestone – the detection of a single electron spin (a single dangling SiO2 bond). This was actually designated as the AIP's "Top Physics Story of 2004," and provided the first means of conducting atomic resolution electron spin resonance mapping of labeled molecules and cells. The research is now on schedule to attain single nuclear spin detection by 2010, a goal that will require another three order of magnitude improvement in sensitivity. At present, conventional MRI images require a trillion or more nuclei to get a sufficiently strong signal. However, once the sensitivity of the MRFM achieves single nuclear spin detection it will afford true atomic-resolution MRI (magnetic resonance imaging), and will permit for 3-D determination of the exact chemistry and structure of individual molecules, molecular assemblies and cellular structures. This will be a major analytical breakthrough that will revolutionize the fields of nanotechnology and biotechnology, and in particular will open the way for designer pharmaceutics, pathogen countermeasure development, and even quantum computing.

Title: Hingeless, Bearingless Rotor Systems

Performer/Institution: Prof. Inderjit Chopra, U. Maryland, Army Rotorcraft Center of Excellence

Timeframe: September 1989–October 1996

In the early 90's the concept of composite hingeless, bearingless rotor hubs to replace conventional articulated rotors was conceived. Such a design appeared to offer significant performance improvements along with greatly reduced parts count (with attendant reliability and maintainability improvement). Unfortunately, the design of these hubs was not possible at the time since the blade articulation is achieved by the elastic flapping of a structural beam, a design known to be susceptible to aeromechanical instabilities. Recognizing the potential of such a configuration, ARO supported Prof. Inderjit Chopra of the University of Maryland to develop an analysis procedure for flap-lag, pitch-flap, and ground and air resonance stability for composite hingeless, bearingless rotor systems. The analysis was based on finite element theory in space and time and covered both the hover and forward flight regimes. It incorporated comprehensive unsteady aerodynamics and state of the art analysis techniques. Systematic validation studies were conducted with flight test and wind tunnel data. These studies demonstrated the performance benefits of such a configuration, and as a result almost every modern rotorcraft hub features hingeless, bearingless hubs, with their design performed using analysis techniques pioneered by Professor Chopra.

Title: Novel Physics-Based Deicing and Anti-Icing Methods
Performer/Institution: Victor Petrenko, Dartmouth University
Timeframe: April 1999–June 2003

This ARO supported basic research investigated the fundamental physics of ice adhesion and developed several novel deicing and anti-icing methods. The three mechanisms contributing to ice adhesion were identified and studied theoretically and experimentally: electrostatic interactions between the electrical charge at the ice surface and the charge induced on a solid substrate; hydrogen bonding between water molecules and substrate atoms; and Liftshitz-van der Waals dispersion forces. Several revolutionary deicing and anti-icing technologies were invented, developed, and tested based upon this new understanding of ice adhesion: a self-assembling mono-layer coating that drastically reduces adhesion of ice to metals, an ice-electrolysis deicer, a high-frequency deicer, a pulse electrothermal deicer, a heat-storage deicer, a lossy-dielectric deicer for high-voltage power lines, and a HF-deicier for power lines. Three novel electrical methods capable to either decrease or increase friction on snow and ice also were invented and developed.

Title: GaAs Electronics—Monolithic Microwave Integrated Circuits (MMICs)
Performers: Nick Holonyak, Steve Forrest, Dan Tsui, George Haddad, Cliff Fonstad, Robert Dutton, Aristos Christou, Stephen Gedney, Michael Steer
Institutions: Illinois at Urbana Champaign, Princeton, Michigan, MIT, Stanford, Maryland, Kentucky, North Carolina State
Timeframe: 1982–2001

In the 1980s and 1990s the ARO made a significant contribution to the creation of theoretical models, processing techniques, and computer aided design (CAD) for the technology that forms the backbone of today's telecommunication industries, that is GaAs Monolithic Microwave Integrated Circuits or MMICs. In particular, ARO funded projects involving Path Integral, Monte Carlo, Wigner and Density Matrix theory as well as transport phenomena and electron-phonon scattering to provide the theoretical underpinnings for GaAs devices. Projects in growth via MOCVD, MBE, and LPE as well as processing through plasma etching led to rudimentary structures of sufficient quality to persuade significant DARPA funding with ARO oversight. These large DARPA programs produced state of the art High Electron Mobility Transistors (HEMTs) and resonant tunneling diodes (RTDs) using the GaAs family of materials. These were the critical circuit elements used in MMICs. In parallel to the device fabrication, ARO also funded projects in computer aided design of integrated circuits which became widely used by the academic and commercial communities and were used to create the monolithic designs for the microwave integrated circuits. Thus a combination of ARO's programs in theory, growth, processing, and circuit design led to the first MMICs. Initially, MMICs were only used in military and space systems and included communication radios (SINCGARs), X-band radar (Patriot), and

L-band SAR. After the early devices, ARO continued to sponsor projects in CAD and device modeling and this work helped to mature the technology and contributed to the explosion in commercial telecom technology, as characterized by the proliferation of cell phones today.

Title: Micro Active Flow Control

Performers/Institutions: Mr. Anthony McVeigh and Dr. James McMichael, Boeing Helicopter and Georgia Tech Research Institute

Timeframe: September 1999–August 2007

Researchers in the early 90's at a number of institutions around the world discovered that MEMS-based actuators creating tiny jets of air could be used to control flow separation in laboratory scale low-speed flow applications. The implication of this in practical engineering applications was tremendous: tiny control forces could be inserted into the flowfield to induce large overall changes. However, adoption of this technology was hindered by its failure to be demonstrated under realistic flow conditions. Recognizing the need to show the effectiveness of this concept for real defense applications, program managers at ARO, AFOSR [Air Force Office of Scientific Research], and DARPA initiated a program for such demonstrations. ARO managed the key research efforts under this program that demonstrated significant performance improvements: (1) a download alleviation effort on the Army/NASA XV-15 tilt-rotor, and (2) a dispersion reduction effort on an Army M203 40 mm grenade. As a result of these advances, Army laboratories have begun major programs for dynamic stall control on helicopter rotorblades, drag reduction for modern Army rotorcraft, and precision munitions.

APPENDIX B

Nobel Prize Scientific Research Supported by the Army Research Office (Reference)

1964

Physics: Charles H. Townes—fundamental work in the field of quantum electronics that has led to the construction of oscillators and amplifiers based on the maser-laser principle.

1972

Physics: John Bardeen, Leon Cooper, J. Robert Schrieffer—developed theory of superconductivity, usually called the BCS theory.

1973

Physics: Brian D. Josephson—theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena generally known as the Josephson effects.

Leo Esaki—experimental discoveries regarding tunneling phenomena in semiconductors and superconductors.

1976

Chemistry: W. M. Lipscomb—studies on the structure of boranes illuminating problems of chemical bonding.

1979

Chemistry: Herbert C. Brown—development and use of boron- and phosphorous-containing compounds, respectively, into important reagents in organic synthesis.

1981

Physics: Arthur Schawlow—contributions to the development of laser spectroscopy.

N. Bloembergen—non-linear optics.

1989

Physics: Hans Dehmelt—development of the ion trap technique.

1996

Chemistry: Richard Smalley—discovery of Fullerenes.

1997

Physics: Steve Chu, Bill Phillips—laser cooling and trapping atoms.

1998

Physics: Daniel Tsui—discovery of a new form of quantum fluid with fractionally charged excitations.

2000

Chemistry: Alan Heeger, Alan MacDiarmid—discovery and development of conductive polymers.

Physics: Herbert Kroemer—developing semiconductor heterostructures used in high-speed and opto-electronics.

2001

Physics: Eric Cornell, Carl Wieman, Wolfgang Ketterle—achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates.

2004

Medicine: Linda Buck—odorant receptors and the organization of the olfactory system.

2005

Chemistry: Robert Grubbs, Richard Schrock—development of the metathesis method in organic synthesis.

Physics: Roy Glauber—quantum theory of optical coherence.

National Medal of Science Recipients Who Have Been Army Research Office Investigators

2006	Daniel Kleppner, Massachusetts Institute of Technology
	Robert S. Langer, Massachusetts Institute of Technology
2005	Carl de Boor, University of Wisconsin
1999	Leo Kadanoff, University of Chicago
1998	George M. Whitesides, Harvard University
1997	Shing-Tung Yau, Harvard University
1996	C. Kumar N. Patel, University of California, Los Angeles
1995	Hans G. Dehmelt, University of Washington
	Herman A. Haus, Massachusetts Institute of Technology
	Louis Nirenberg, Courant Institute, New York University
	Alexander Rich, Massachusetts Institute of Technology
1994	Frank Press, National Academy of Sciences
1993	Norman Hackerman, Rice University
1992	Calvin F. Quate, Stanford University
	John R. Whinnery, University of California, Berkeley
	Allen Newell, Carnegie Mellon University
1991	Arthur L. Schawlow, Stanford University
	H. Guyford Stever, Washington, D.C.
1990	Nick Holonyak, Jr., University of Illinois
1989	Harden M. McConnell, Stanford University
	Joshua Lederberg, Rockefeller University
1988	Paul C.W. Chu, University of Houston
	Stanley N. Cohen, Stanford University
1987	James A. Van Allen, University of Iowa
	Ernst Weber, Polytechnic Institute of New York
1986	Carl S. Marvel, University of Arizona
	Harry B. Gray, California Institute of Technology
1983	Robert J. Schrieffer, University of Florida
	Richard N. Zare, Stanford University

1982	Charles H. Townes, University of California, Berkeley
1979	Emmett N. Leith, University of Michigan
1975	Joseph Hirschfelder, University of Wisconsin
1974	Nicholas Bloembergen, Harvard University
1973	John W. Tukey, Princeton University
1969	Herbert C. Brown, Purdue University
1966	Henry Eyring, University of Utah
1965	John Bardeen, University of Illinois
	Peter J.W. Debye, Cornell University
1964	Robert B. Woodward, Harvard University

APPENDIX D

Army Research Office Mission Statement (Reference)

The U.S. Army Research Office (ARO) mission is to serve as the Army's premier extramural basic research agency in the engineering, physical, information and life sciences; developing and exploiting innovative advances to insure the Nation's technological superiority. Basic research proposals from educational institutions, nonprofit organizations, and private industry are competitively selected and funded. ARO's research mission represents the most long-range Army view for changes in its technology. ARO priorities fully integrate Army-wide, long-range planning for research, development, and acquisition. ARO executes its mission through conduct of an aggressive basic science research program on behalf of the Army so that cutting-edge scientific discoveries and the general store of scientific knowledge will be optimally used to develop and improve weapons systems that establish land force dominance. The ARO research program consists principally of extramural academic research efforts consisting of single investigator efforts, university-affiliated research centers, and specially tailored outreach programs. Each approach has its own objectives and set of advantages. Programs are formulated in consultation with the Army Research Laboratory Directorates; the Research, Development and Engineering Command's Research, Development and Engineering Centers; the Army Medical Research and Materiel Command; the Army Corps of Engineers; and the Army Research Institute for the Behavioral and Social Sciences. The programs are also jointly coordinated and planned through the Defense Science and Technology Reliance process under the Basic Research Panel.

Functions:

- Accelerating research results transition to applications in all stages of the research and development cycle.
- Strengthening academic, industrial, and nonprofit laboratories research infrastructures which serve the Army.
- Focus on those research topics that support technologies vital to the Army's future force, combating terrorism and new emerging threats.
- Directing efforts in research areas relating to new opportunities for Army applications and which underscore the role of affordability and dual-use, especially as they provide new force operating capabilities and emerging threats.

- Leveraging the science and technology of other defense and Government laboratories, academia and industry, and appropriate organizations of our allies.
- Fostering scientist and engineer training in the disciplines critical to Army needs.
- Actively seeking creative approaches to enhance education and research programs at historically Black colleges and universities and at minority institutions.

APPENDIX E

Army Research Laboratory Mission Statement (Reference)

The Army Research Laboratory (ARL) is the Army's corporate basic and applied research laboratory. Our mission is to provide innovative science, technology, and analysis to enable full-spectrum operations. ARL consists of the Army Research Office (ARO) and six Directorates—Weapons and Materials, Sensors and Electron Devices, Human Research and Engineering, Computational and Information Sciences, Vehicle Technology, and Survivability and Lethality Analysis. The Army relies on this ARL Team for scientific discoveries, technologic advances, and analyses to provide warfighters with capabilities to succeed on the battlefield.

APPENDIX F

Army Research, Development and Engineering Command Mission Statement (Reference)

MISSION: To develop, integrate, and sustain decisive technology-enabled capabilities to ensure the dominance of our Warfighters today and in the future.

VISION: Be the world leader in rapid, innovative research, development and engineering for the Warfighter.

INTENT: The Commanding General of the U.S. Army Materiel Command (AMC) established the U.S. Army Research, Development and Engineering Command (RDECOM), as a new major subordinate command within AMC. This new command will restructure core in-house capabilities now so we can fully exploit the enormous potential that resides in research activities around the world. RDECOM will respond rapidly by integrating, maturing and demonstrating emerging technologies to field the right equipment, in the shortest time, for our Soldiers.

RDECOM is an Army focal point for developing and accelerating innovative technology and sound engineering solutions that provide our U.S. forces with decisive and dominant capability where they need it, when they need it. RDECOM is unparalleled in its depth and breadth of technical capability, innovation and dedication to provide our U.S. forces with the best technology, today and in the future.

RDECOM provides the full spectrum of basic research, development, engineering and analysis of Warfighter systems, from concept to capability. Headquartered at Aberdeen Proving Ground in Maryland, the Command has laboratories and research, development and engineering centers throughout the country and representatives throughout the world. The Command is home to more than 14,000 military and civilian personnel, who work to harness the potential of research, development and engineering for the Warfighter on a daily basis.

RDECOM integrates all the technologies developed within RDECOM labs and centers to eliminate duplicated efforts between the nine RDECOM subordinate elements. Headquarters evaluates technology integration and provides Warfighters and decision makers with essential mission information and potential capabilities of the latest technologies. With high-speed resources including the Integrated Product Teams (IPT), Army International Technology Centers, Rapid Equipping Forces

(REF), Rapid Acquisition Process and the Field Assistance in Science and Technology (FAST) program, RDECOM maximizes its capabilities to provide direct support to current operations by providing technology solutions and coordinating with acquisition organizations.

APPENDIX G

Panel Members

Robert A. (Bob) Beaudet

Robert A. Beaudet has been a full professor of physical chemistry at the University of Southern California since 1971. He was chairman of the Chemistry Department from 1979 to 1983. After that, he returned to full-time research and teaching. He retired from the University in 2005 after 42 years and is now Emeritus Professor of Chemistry. He remains on the staff as a part-time senior engineer at the NASA Jet Propulsion Laboratory in Pasadena, California.

Bob received his undergraduate training at Worcester Polytechnic Institute in Worcester, Massachusetts, in 1957. His graduate work was conducted in microwave rotational spectroscopy under Professor E. Bright Wilson at Harvard University, where he was awarded an A.M. degree in 1960 and a Ph.D. in 1962. He has been on the faculty at the University of Southern California since 1963, where he actively carried out basic research in molecular spectroscopy, molecular structure determinations, and internal rotation and motions in molecules and van der Walls complexes. His outside interests include energetic materials, armor, and all aspects of chemical warfare, detection and monitoring, destruction of chemical munitions, and related treaty issues

He was a National Science Foundation predoctoral fellow from 1957 to 1961 while at Harvard and was awarded a National Research Council postdoctoral fellowship in 1962. He received an Alfred P. Sloan Foundation Fellowship in 1966 and an Alexander Von Humboldt Special American Award in 1975. He also was a guest professor at the Max Planck Institute for Quantum Electronics in Garching, Germany, in 1979.

Bob has been extensively interested and involved in advisement for the U.S. government. From 1968 to 1979, he was a member of the U.S. Army Science Advisory Panel, later renamed the Army Science Board, where he participated in numerous ad hoc studies. From 1969 to 1976, he was a member of the Presidential Science Advisory Council Panels on Ground Warfare, on Narcotics Enforcement, and on NATO. He has also served on a Defense Science Board Study as a consultant. He also served on a Science Advisory Committee to the Bureau of Narcotics and Dangerous Drugs. He was on the staff of Arroyo Center at the NASA Jet Propulsion Laboratory in 1983–

1985, where he was involved in a study that demonstrated that passive remote sensing would be effective for CW Treaty Verification and for detecting nonpersistent gas clouds from either a remotely piloted vehicle or a spacecraft.

Bob has also served on numerous National Academy of Science/National Research Council (NAS/NRC) panels, including a panel for the Detection of Chemical Agents, the Panel on Energetic Materials, and NAS's Oversight Advisory Committee of the Army Chemical Research, Development and Engineering Center at Edgewood, Maryland. He was also a member of the Technical Advisory Committee for CW Treaty Verification Group at Army Chemical Biological Defense Command (CBDCOM), Edgewood Arsenal. He was a full member of the NAS/NRC's Board on Army Science and Technology (BAST), where he oversaw the CW Stockpile Committee and the Alternative Technologies Study Panel. Since 1996 he has served and continues to serve as chair of several NRC committees that oversee the Assembled Chemical Weapons Alternative (ACWA) program to destroy the chemical munitions at Pueblo Chemical Depot CO and at Blue Grass Army Depot in Kentucky by chemical neutralization.

He was cochairman of the BW/CW Competency Panel in a recent Defense Science Board Summer Study on DoD Responses to Transnational Threats.

Until 2008, he was also a member of four Director's Review Committees at the Lawrence Livermore National Laboratory. These include the directorates for Nonproliferation, Arms Limitation and Internal Security, for Chemical and Material Science, for Engineering, and for Energy and Environment.

Bob remains a staff member of NASA's Jet Propulsion Laboratory (JPL) where, for ten years, he participated in JPL's program supporting the Army's Advanced Artillery System (Crusader), a system using liquid propellant. Recently he has supported the microbiologists in Mars-related programs and missions.

Siddhartha (Sid) Dalal

Siddhartha (Sid) Dalal, Ph.D., is the Senior Advisor to the President for Technology at the RAND Corporation in Santa Monica, California. Sid conducts research in various units and helps develop new initiatives regarding the scientific and technological dimensions of current and emerging policy challenges.

Prior to joining RAND in 2007, Sid was at Bell Laboratories, followed by Bellcore/SAIC/Telcordia Technologies, where he served as chief scientist and executive director. Later, as Vice President of Research at Xerox, he was in charge of Xerox's worldwide imaging and software services research.

In addition to creating innovative technologies for businesses, Sid has coauthored more than 70 publications, several patents, and two National Academy of Sciences monographs covering the areas of software and network engineering, risk analysis, statistical and econometrics modeling, data/document mining, and machine learning.

He has been a recipient of numerous awards, including for the risk analysis work on the Space Shuttle Challenger disaster on behalf of the National Research Council, for the invention of combinatorics-based software testing technology from IEEE and ASQ, and the Rochester Distinguished Scholar medal from the University of Rochester.

Sid holds a B.S. from the University of Bombay, and an M.B.A. and Ph.D. in statistics from the University of Rochester.

Jay Davis

Jay Davis is a nuclear physicist trained at the Universities of Texas and Wisconsin. During his three-decade career at the Lawrence Livermore National Laboratory, he built accelerators for research in nuclear physics and for materials science in support of the fusion program. He also founded the Center for Accelerator Mass Spectrometry, making possible the application of isotopic tracing and tagging tools to a wide range of problems in the geosciences, toxicology, nutritional sciences, oncology, archaeology, and nuclear forensics. In the national security component of his career, he worked to develop techniques for arms control treaties, was a senior member of the NEST program, served as a nuclear inspector in Iraq for the United Nations Special Commission (UNSCOM) after the First Gulf War, and then served as the founding Director of the Defense Threat Reduction Agency (DTRA). As Director of DTRA, he merged three DoD organizations to create DoD's operating and technical focus for dealing with all aspects of weapons of mass destruction. His continuing research and national security interests are in the areas of nuclear forensics, renewal of the U.S. nuclear force, counterterrorism, and management of change in organizations.

In retirement from Lawrence Livermore National Laboratory since 2002, Jay now grows grapes, and consults and serves on a variety of foundation and advisory boards. These include the Board on Army Science and Technology and the Nuclear and Radiation Studies Board of the National Academy of Sciences, and the Threat Reduction Advisory Committee for the Department of Defense. He is a member of the Panel on Public Affairs of the American Physical Society. He has for more than 15 years been a Member of the Board of Directors of the Hertz Foundation, serves on the Distinguished Advisory Board of the American Committees on Foreign Affairs, and chaired the Executive Advisory Board for the Micro-Scale Immune Systems Laboratory for Sandia National Laboratory. In the past, he has served on the Board of Trustees of ANSER Corporation, the University of Chicago Board of Governors for Argonne National Laboratory, and a variety of advisory and review boards for the Livermore, Berkeley, and Los Alamos National laboratories.

Among his honors are Phi Beta Kappa, an AEC Postdoctoral Fellowship, Fellowship in the American Physical Society, and being picked as one of the Centennial Lecturers for the APS's 100th Anniversary Year. Davis was twice awarded the Distin-

guished Public Service Medal of the Department of Defense, DoD's highest civilian award. He has more than 80 technical publications in a variety of scientific and technical areas and several patents that form the basis for analytical companies in bioscience and the pharmaceutical sciences. Married to Mary McIntyre Davis for 45 years, he has two children: Kathleen, an archaeologist married to Jay King, also an archaeologist, and Robert, a geologist, married to Theresa Davis, a teacher. They have four grandchildren: Malcolm King, Melinda Davis, David King, and Jack Davis. All work in the Davis-King vineyard at harvest.

Gilbert Decker (Chairman)

Gil has been a private consultant and director for various high-tech and defense corporations since September 2001. Prior to that, Gil was the executive vice president of engineering and production for Walt Disney Imagineering from 1999 to 2001 and Assistant Secretary of the Army for Research, Development and Acquisition from 1994 to 1997. He also served as the president and CEO of Acurex Corporation and, prior to that, Penn Central Federal Systems companies.

Gil has served as the director of Alliant Techsystems, Allied Defense Group, Digital Fusion, Inc., and numerous other organizations. In addition, he has been a member of the Defense Science Board, the Army Science Board, the National Academy of Sciences/National Research Council Board on Army Science and Technology, and various other government and public organizations.

Gil served as a captain in the U.S. Army from 1958 to 1964 and a colonel in the U.S. Army Reserves from 1964 to 1989, when he retired. He holds a B.E.S. in electrical engineering from the Johns Hopkins University and an M.S. in operations research from Stanford University.

He is married to Sandy Decker, a former city council member and mayor of Los Gatos, California, where they both currently reside. Gil maintains an active interest in national security and defense, the local government of Los Gatos, and youth science education.

William H. (Bud) Forster

Bud Forster established his management consultancy business after retiring from Northrop Grumman Corporation in 2004. As vice president of Northrop Grumman's Land Combat Systems, Forster was responsible for systems and manufacturing development, production, and fielding of Army and land combat–related systems in the areas of air and ground fire control radars, precision guided weapons, unattended vehicles and sensors, and night vision devices.

Forster joined Northrop Grumman (formerly Westinghouse) in October 1995 after a long and distinguished career with the U.S. Army. He is a graduate of the U.S. Army Aviation School, the U.S. Navy Test Pilot School, and the U.S. Air Force Air War College. He served two tours of duty in Vietnam and held numerous positions of responsibility during 30 years of military service.

Earlier in his career, Forster served with the National Aeronautics and Space Administration in Houston, Texas. In recent years, he served as the project manager for both the Army Helicopter Improvement Program and the Apache Advanced Attack Helicopters, Deputy Commanding General of the Army Aviation Systems Command, and Program Executive Officer for Combat Aviation Systems.

Forster's other notable assignments include Army Director of Requirements; Chairman of the American, British, Canadian, and Australian Armies' Washington Standardization Office; Commanding General of the U.S. Army Operational Test and Evaluation Command; and, most recently, as Director, Army Acquisition Corps and Military Deputy to the Assistant Secretary of the Army for Research, Development, and Acquisition. At the time of his retirement, Forster held the rank of lieutenant general.

During his career, Forster received numerous decorations and commendations, including two Distinguished Service Medals, two Legions of Merit, two Bronze Star Medals, two Meritorious Service Medals, the Distinguished Flying Cross, and 16 Air Medals.

In 1993, Forster, who holds a B.S. in chemistry from the University of Alabama and a Ph.D. in nuclear chemistry from the University of California, was recognized for his academic and technical achievements by election to membership in the Russian Academy of Natural Sciences. In 1995, he received the American Helicopter Society Special Award for Lifetime Achievement in advancing vertical flight technology. He was named a fellow of the American Helicopter Society in 1997, and in 2004 he was elected president of the society and became chairman of the society's board in 2005. He served as chairman of the National Academy of Science Board on Army Science and Technology from 1996 through 2001, and is a member of the Army Science Board, the American Physical Society, the National Aeronautic Association, and the Army Aviation Association.

George T. Singley III

George T. Singley III is currently a member of the Commission on Army Acquisition and Program Management in Expeditionary Operations and a vice chairman of the Association of the U.S. Army.

Since retiring from Science Applications International Corporation (SAIC), Singley has served as a defense consultant. From 2003 to 2007, he was president of the

$2 billion per year, 7,500-employee-strong Engineering, Training and Logistics Group of Science Applications International Corporation (SAIC). From 1998 to 2003, he was president and CEO of Hicks and Associates, Inc., a wholly owned subsidiary of SAIC.

From 1995 to 1998, he served in OSD as Acting Assistant to the Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs; Acting Director of Defense Research and Engineering; Principal Deputy Director Defense Research and Engineering; and Principal U.S. Representative to the NATO Research and Technology Board and The Technical Cooperation Program (TTCP) of the United States, United Kingdom, Canada, Australia, and New Zealand.

Prior to 1995, Singley served as Army Deputy Assistant Secretary for Research and Technology and Chief Scientist; Program Executive Officer for Combat Support Aviation; Assistant Director of Army Research and Technology in the Office of the Secretary of the Army; and aerospace engineer with the Army Aviation Systems Command.

He is past vice chairman of the National Academy of Sciences Board on Army Science and Technology, former national vice president of the Army Aviation Association of America, and former member of the Army Science Board. He is an honorary fellow and past chairman of the American Helicopter Society (AHS) Board of Directors.

His awards include Distinguished and Meritorious (twice) Executive Presidential Rank Awards; Secretary of Defense Distinguished Public Service, Distinguished Civilian Service, and Meritorious Civilian Service Medals; AHS Grover Bell Award for rotorcraft research; Old Dominion University Engineer of the Year for 2008; and University of Delaware Distinguished Engineering Alumnus of 1991.

Singley received his M.E. in mechanical engineering from Old Dominion University (1977), his M.B.A. from the College of William and Mary (1971), and his B.E.A. in mechanical engineering from the University of Delaware (1968).

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